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CONTROLLED ENVIRONMENT FACILITIES: A
SURVEY

John M. Henderson

Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

1961

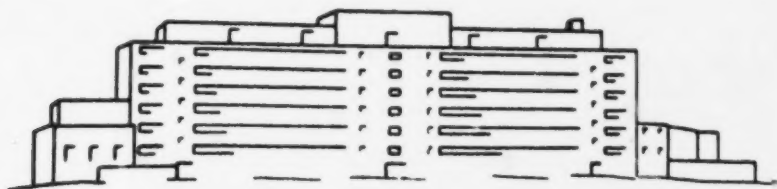
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A Survey



The Robert A. Taft
Sanitary Engineering Center

TECHNICAL REPORT

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**U. S. DEPARTMENT OF HEALTH,
EDUCATION, AND WELFARE**
Public Health Service

CONTROLLED ENVIRONMENT FACILITIES

A Survey

By

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U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Bureau of State Services
Division of Water Supply and Pollution Control

Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

1961

CENTER PUBLICATIONS

The Robert A. Taft Sanitary Engineering Center is a national laboratory of the Public Health Service for research, training, and technical consultation in problems of water and waste treatment, milk and food safety, air pollution control, and radiological health. Its technical reports and papers are available without charge to professional users in government, education, and industry. Lists of publications in selected fields may be obtained on request to the Director, Robert A. Taft Sanitary Engineering Center, Public Health Service, Cincinnati 26, Ohio.

FOREWORD

Why do we need controlled environment facilities?

With the rapid industrial and residential metropolitan growth in recent years, research in water supply and pollution problems extends to new dimensions. Algal blooms in surface water supplies become a matter of concern, while in waste stabilization ponds the controlled growth of algal species is a matter of utility. In the depths of reservoirs the effects of stratification are found to influence water quality. Downstream, the heat released from power plants and in industrial cooling waters is referred to as "thermal pollution."

In areas where supplies are at a premium, interest has developed in methods of conserving water by reducing evaporation losses. Where supply is threatened by pollution, a need arises to study the fate of pesticides and microorganisms in soil and in water under varying conditions of environment. The influence of environmental conditions in waste disposal and waste treatment in top soils invites investigation. At every turn, the studies of the research scientist in the complex of environmental circumstances are greatly intensified.

With this increasing attention to environmental aspects of water quality, interest has developed in the feasibility of using controlled environment facilities in this research. Such facilities may make possible acceleration of important developments, whether the research relates to special variables under controlled conditions, or whether the need is to simulate a natural complex consistently over a period of time.

Design requirements of controlled facilities must be approached thoughtfully to achieve the desired results. Accordingly the Division of Water Supply and Pollution Control, Research Branch, enlisted the services of Mr. John M. Henderson to survey some of the facilities of this type available in the United States. The present report summarizes his notes and observations. It makes plain that much planning and development remain to be done before a controlled environment facility of the sort we need can become a reality.

BERNARD B. BERGER
Chief, Research Branch
Division of Water Supply
and Pollution Control.

June 1961

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SUMMARY

INTRODUCTION

A survey of controlled environment facilities was performed for the Research Branch, Division of Water Supply and Pollution Control, Robert A. Taft Sanitary Engineering Center, Public Health Service.

The survey included locating, examining and evaluating the performance of special research facilities designed to provide any desired combination of temperature, relative humidity, radiation covering the daylight range of the spectrum, wind action, and barometric pressure (simulated altitude). Numerous field visits and extensive literature research were carried out. Evaluation was directed to assessment of installation and operating costs, analysis of usefulness, and a report with general conclusions and recommendations on the practicality of such special facilities.

PRINCIPAL CONSIDERATIONS

Solar Irradiation

Simulated solar irradiation is considered the most important of the specified controlled variables, because of the infinite variety of intensity and quality patterns of natural solar irradiation.

Quality and Intensity Patterns of Solar Irradiation

In the interest of simplification, the Angstrom unit is mainly employed in this report as the unit of wave length and the langley as the intensity unit. These units and the solar constant are defined. The foot candle is mainly employed in reporting light intensity values in the visible spectrum for the plant growth room facilities visited.

Variations in the quality and intensity of solar irradiation reaching the ground surface, due to atmospheric scattering, diurnal variations in air mass, filtering effects of ozone and water vapor, effects of altitude, aridity, latitude and overcast, are presented and discussed. In a summary of this section, several graphs are presented. These deal with intensity values relative to wave length at the ground surface and at the edge of the earth's atmosphere for Parry Moon's "Standard Solar Irradiation Curve" under air mass 2 conditions and under other standard conditions assumed by him.

Solar Irradiation Requirements of Plants

Thermal energy requirements of plants are not considered of critical interest in this study because the energy they receive from solar irradiation does not need to be wave-band specific.

The photobiologic energy responses and requirements are subdivided into two categories:

Photosynthesis and non-chlorophyll photochemical pigment activity.

The primary energy source for chlorophyll pigments in photosynthesis is irradiation in the violet-blue region (4000 to 5100 AU) and in the orange-red region (6100 to 7000 AU). Plants have many other pigments which are excited by radiant energy in various wave band regions, not all of which are in the visible spectrum. These non-chlorophyll pigments are mainly of a hormone-response type in the control of plant development. The presence of specific pigments and their relative predominance varies with different plant species, especially in algae of different colors. There is also a two-way energy exchange relationship between chlorophyll pigments and these other pigments.

Responsewise, plants "see" the logarithm of solar light intensity, and solar irradiation values rapidly climb to plant saturation levels during the course of a clear day.

Figure 5 shows the over-all spectral light quality requirements of plants as calculated by plant scientists.

Solar Irradiation Simulation with Lamps

Although conventional lamps do not faithfully simulate solar irradiation, satisfactory growth of terrestrial plants is obtained with them in plant growth rooms. By conventional lamps is meant fluorescent and tungsten filament lamps in widespread use for general lighting purposes. The characteristics of these lamps and of some special types of lamps are described.

Other Considerations

This section is mainly concerned with the temperature and relative humidity variables. The relatively wide diurnal variations which take place under ambient conditions during clear days in temperature and relative humidity and the interrelationship of these two variables are described. The question is raised whether accurate control of air temperature and relative humidity is essential or even desirable in a facility where conditions as they occur in nature are to be simulated.

Climatologic Data

Information collected by the Weather Bureau at 300 "first order" stations is briefly cited. The completed 5-year summaries of hourly observations and the 10-year summaries under preparation are noted. The Weather Bureau's solar radiation network and ozone stations are more specifically described because they are less well known.

OBSERVATIONS

Resumés of some of the facilities visited are given.

Information on type, location, size, cost and design ranges of controlled environment facilities is presented in four tables.

Operating and construction costs are discussed and evaluated. Construction costs of facilities visited or projected ranged from \$3000 to \$6 million. These are analyzed on a unit space and functional basis. Two general conclusions are reached.

The different methods of air temperature and humidity control encountered are described and evaluated.

Special attention was given to an attempt to locate a facility involving biological activity in a water-holding model. This effort failed to achieve significant results. With one exception, indoor algal growth facilities were test tube or flask size. The exception was a proposed facility in Israel with a pond 1 cu. m. in size.

It is postulated that an algae tank simulating the natural conditions of a pond would require rather high intensity irradiation in order to obtain light penetration to an adequate depth. The irradiation level needed, however, probably would not exceed that possible with fluorescent lamps. The capability of growing all types of algae, including marine species, might require a facility with a rather broad spectral quality pattern, but probably not in excess of that provided by fluorescent lamps supplemented by incandescent filament lamps.

It is also considered that the production of waves in a water-holding model would require mechanical wave-making equipment. The type of equipment needed to create ripples in a water-holding model was not determined.

A sixth controlled variable (mechanical wave-making), has been considered in this survey in addition to the five specified variables. This review has bearing on all six.

In no facility which could be located by inquiry of many sources were the six variables or the five specified variables employed in combination. Three were commonly found together -- simulated solar irradiation, temperature and relative humidity control. Associated with these was air movement within the limits of conventional air-conditioning equipment. The feasibility of combining these is accordingly self-evident.

The foregoing are rated as three-and-a-half

variables, with partial credit allowed for air movement. Within prescribed limits, it is considered practical also to include simulated altitude in a single chamber. Mechanical wave-making equipment of a sort could be added if desired. The remaining part-variable (wind as distinguished from air movement) could theoretically be added but its feasibility is uncertain.

Certain subchamber combinations of controlled variables are offered as alternatives to an all-in-one facility.

In considering conjoint development and use of a controlled environment facility, one plan would be reliance on a contract facility to meet needs for extreme range of a particular variable or for a rarely needed controlled variable.

Another plan would be one of shared use, by all elements of the Sanitary Engineering Center or also by added elements of the Bureau. Under this concept, facilities routinely used by any specialized group would be individual for that group, but several groups would have joint use of facilities with rarely needed variables or ranges and common central mechanical equipment, mechanical operating staff, repair facilities and instrumentation specialists.

GENERAL CONCLUSIONS

The feasibility of controlled environment facilities for a rather wide variety of investigations is considered established by both long-term use and current expansion of sub-installations. The issue is not feasibility *per se* but the feasibility of application to a particular situation.

Other conclusions reached are that:

Natural conditions need to be simulated only approximately if nature is to be "simulated" for model study purposes. This statement is with respect to biologic processes and their controlling environmental influences.

A facility should be as flexible and as simple in design and operation as possible, consistent with use requirements.

Specialized planning and design are essential.

APPENDIX

Emphasis in the text of this report has been placed on evaluation rather than on particulars. Detailed notes on facilities and offices visited and other information obtained by telephone, mail and literature research are recorded in the Appendix.

CONTROLLED ENVIRONMENT FACILITIES

A Survey

INTRODUCTION

This report contains information acquired in a survey of controlled environment facilities, together with pertinent findings and conclusions. The survey was performed for the Research Branch, Division of Water Supply and Pollution Control, Robert A. Taft Sanitary Engineering Center, U.S. Public Health Service, November 20, 1960, to March 1, 1961.

Information on existing and proposed controlled environment facilities, on the state of the art, and on basic data and background needed for general and technical perspective, evaluation, and feasibility appraisal, was acquired by visits to existing and planned facilities, conferences in the Washington, D. C., area with Federal agency representatives, conferences and correspondence with University faculty members and investigators, and correspondence with manufacturers of prefabricated controlled environment facilities and components. Literature research was also a productive source of information, and both public and technical libraries were utilized.

Field travel included visits to Washington, D. C. and environs; Lafayette, Indiana; St. Louis, Missouri; Dallas, Texas; Phoenix and Tucson, Arizona; and Atlanta, Georgia.

The controlled variables under investigation included (1) temperature, (2) relative humidity, (3) simulated altitude, (4) simulated solar irradiation, and (5) wind. A sixth variable (water-waves) was added as a possible option to the "wind" variable.

The facilities visited were chosen largely on the basis of information and advice obtained in the Washington, D. C., area. The advisors interviewed there stressed the technical importance of the solar irradiation variable and furnished information on the location of multi-variable facilities employing partially simulated solar irradiation. For this reason more attention was paid to irradiation than to other variables, but the temperature and relative humidity were not overlooked. About 50 million structures in the United States are provided with one type or another of temperature control, and many have some degree of relative humidity control, evidence that the state of the art is more developed and perhaps more systematized for these two variables than for the others.

PRINCIPAL CONSIDERATIONS

Baselines were required for appraising and evaluating the operating characteristics of facilities surveyed. That is, the nature and extent of required control of variables had to be considered in relation to the possible design of a controlled environment facility for the Sanitary Engineering Center.

Solar Irradiation

The great changes which take place in solar irradiation from sunrise to sunset and from day to day due to weather conditions, the selective filtering effects of the earth's atmosphere, the lesser influences of altitude and latitude, and the selective photobiological processes of living plants, pose complex questions as to what are the proper baseline values for an artificial, controlled environment, and also the extent and character of irradiation programming requirements.

Finding answers to these questions is complicated, as shown, by the wide differences of opinion and practice encountered during the survey. Moreover, two distinctly different plant growth environments would be involved in an SEC facility -- a soil-air environment and an aquatic environment.

The following discussion of solar irradiation is intended to approach answers to these questions:

1. What is the nature of solar irradiation with respect to intensity and quality values and in what manner and to what extent do these values vary with time, place and weather?
2. What are the critical needs and values in simulating solar irradiation in order to reproduce natural conditions with respect to:
 - a. Possible damage to physical substances under test?
 - b. Normal growth of terrestrial vegetation?
 - c. Normal growth of aquatic vegetation?

3. What is the state of the art in simulating solar radiation?

Quality And Intensity Patterns Of Solar Irradiation

Units of Measurement

The complete solar spectrum can be portrayed only by resolving solar irradiation into energy values. These energy values may be plotted as the ordinate against wave length as the abscissa of a curve or similarly reported in tabular form. Wave length in the solar spectrum range is generally given in terms of either microns or Angstrom Units (Å or AU), which are readily converted since 1 micron equals 10,000 AU. Solar energy values are given in several different energy units, the more common being langleys (used by the U.S. Weather Bureau in weather reports), watts per sq. meter per micron, gram calories per square centimeter per minute, British thermal units per day per square foot, and ergs per square centimeter per second. For convenience, most energy values in this report are expressed in langleys. A langley is equal to 1.0 gram calories per square centimeter per minute. For comparison, the solar constant as reported in tables and other references in this study is 1.896 or 1.94 langleys, depending on the reference. The solar constant is the energy value of the solar irradiation received at normal incidence at the edge of the earth's atmosphere when the sun is at its mean distance from the earth.

When only the visible spectrum is involved, the lux, lumen or foot-candle is employed as a unit of photo-measurement. These are more or less subjective units, since they refer to what the human eye sees or to what is "seen" by a particular photo-chemical in a light meter. Such values are not the same as what plants "see". However, the foot-candle was commonly used in reporting irradiation values at plant growth rooms visited.

Variables in Solar Irradiation

The base energy value, from which departures in solar irradiation values due to variables are measured, is the solar constant.

A comprehensive review of the many variables which affect solar energy received at ground level under different climatologic, seasonal, and geographic conditions is given by Moon (8). In this article, an attempt was made to establish a standard solar irradiation curve which was proposed as a convenient norm for approximating the solar irradiation actually received at the earth's surface, and as a reference plane for evaluating the amount of departure from the "standard" under various conditions. Its intended significance in meteorology was somewhat comparable to such sanitary engineering design norms as 0.167 lbs. of oxygen demand/capita/day or 100 gcd.

To establish this curve, it was necessary for Moon to explore the variables, and to select certain "average" or "representative" values in order to subtract them from an outer space curve which served as a baseline. This required a discussion of the principal variables.

One variable, however, was so pronounced in its effect and varied so frequently and so universally that it was not possible to resolve it in any single standard curve. This is the effect of air mass on solar irradiation, which varies with the sun's daily passage from horizon to horizon. As a result, the standard curve or table becomes plural and consists commonly of a set of 6 curves. These reflect air mass conditions 0, 1, 2, 3, 4 and 5, with air mass 0 being the baseline and representing solar irradiation at the zenith position at the edge of the earth's atmosphere (i. e., comparable to the solar constant). The other 4 air mass conditions are secant values with the altitude leg of the triangle representing a vertical or zenith line and the hypoteneuse a line drawn from the altitude line at its ground surface intersection to the sun's actual position at a given time of day. Accordingly, air mass 1 represents the radiant energy on a ground surface normal to the sun's rays when the sun is at the zenith, air mass 2 represents an angle of departure of $59^{\circ}-30'$ from the zenith, air mass 3 is $70^{\circ}-30'$, air mass 4 is $75^{\circ}-30'$ and air mass 5 is $78^{\circ}-30'$. It will be seen from an examination of these angles that air mass conditions 1 and 2 are the most significant energy-wise since the sun travels through some 119° of air mass arc in passing from air mass 2 in the

morning, through air mass 1 at noon, and to air mass 2 in the afternoon.

In the introduction to his paper, Moon states: "The radiant energy at normal incidence, received at the surface of the earth from the sun, is subject to wide variations because of the following factors:

1. Variations in the sun itself.
2. Variations in the distance from earth to sun.
3. Differences in atmospheric scattering.
 - a. by air molecules,
 - b. by water vapor,
 - c. by dust.
4. Differences in atmospheric absorption by O_2 , O_3 , H_2O , CO_2 , etc."

Since these four categories are not fully appraised by Moon's article, which was necessarily a summary, the rest of this section draws on background from a number of other sources of information as well. They are listed in the Bibliography. Also, since this summary is more concerned with variables which have a selective effect and generally are less well known, discussion of categories 1 and 2 is passed by.

Of the remaining two, category 3 is considered to be distinctly secondary to category 4 in importance, except possibly in very abnormal situations. One interesting manifestation of category 3, however, is that a limited indirect selective effect appears to take place. Some changes in wave length occur from atmospheric scattering. These changes are always from a higher to a lower energy level and hence represent a shift to the right (i. e., toward longer wave lengths).

The outstanding manifestations of the effect of the absorption phenomenon listed in category 4 are:

1. The narrowed solar spectrum boundaries which are established by absorption effects.
2. The high importance of O_3 and water vapor as radiation filters.

3. The selectivity of the energy absorption by filters in terms of wave length.

The term "boundaries" as used, refers to the wave band boundaries within which possible 99.999% of the total energy received at ground surface is transmitted. That is, the boundaries are those of the meteorologist and may not agree with those of a theoretical physicist, especially an atomic physicist. On the right or long wave length side of the energy curve, the effective boundary is reached at 23,000 AU. Beyond this value, absorption by water vapor (primary) and CO₂ (secondary) becomes so complete that scarcely any solar radiation is transmitted. On the left or short wave length side, the cutoff point is at 2975 AU and is essentially due to absorption by ozone. (The solar spectrum at the edge of the earth's atmosphere covers a much wider wave band range on both sides of these boundaries).

Thus, in a theoretical approach to the evaluation of any controlled environment facility and to the design of such a facility, the potential limits of consideration of solar spectrum simulation are limited to the wave band between about 3000 AU and 23,000 AU. A classification of this range is given below, selected to conform to significant wave band areas involved in the effects of light on plant development and on the deterioration of physical substance.

Category	Wave band (angstrom units)
Solar spectrum reaching earth's surface	2975 - 23,000
Ultraviolet rays reaching earth's surface	2975 - 3900
Spectrum visible to human eye	3900 - 7600
Spectrum involved in plant photobiology for direct photosynthesis	(4000 - 5100 (6100 - 7000
For some other photochemical effects	3150 - 5100
For near-red photochemical effects	5500 - 7000
For short-wave far-red photochemical effects	7000 - 8000
Spectrum significant to plants only for indirect benefit from heat	(5100 - 6100* (8000 - 23,000

* Statement mainly true.

The following data excerpted from Moon's article gives a comparison of solar irradiation energy values for specified short-wave lengths on the right side of the left boundary cutoff point of 3000 AU. The selective filtering effect of ozone at different wave length points is apparent from examination of the table which follows. The total filtering effect of ozone when the sun is directly overhead is shown by the difference in energy values between air masses 0 and 1. The added filtering effect caused by a 2-step increase in air mass is shown by the difference in energy values between air masses 1 and 3. This table is based on a sea-level condition and 2.8 mm of O₃ in the total atmospheric blanket.

Wave length (angstrom units)	Radiant energy values under air mass condition		
	0	1	3
2975	400	0	0
3000	400	50	0
3050	400	90	0
3100	400	175	25
3150	400	260	40
3200	400	330	70

Illustrative of the over-all radiant energy reductive effects of air mass on clear days are values from Moon shown in the following table. The table has been abbreviated to exclude air mass conditions 2, 3, and 4. It is based on values assumed by Moon of 2.8 mm of ozone, 760 mm of pressure, 20 mm of water vapor, and 300 dust particles per cubic centimeter in the atmospheric blanket and is for a ground surface at sea level normal to the sun's rays.

Wave length (angstrom units)	Energy values under air mass condition		
	0	1	5
2900 - 4000	95	40	3
4000 - 7000	540	420	164
7000 - 11,000	365	309	181
11,000 - 15,000	162	95	41
15,000 - 19,000	73	51	35
19,000 - 23,000	87	13	6
Total	1322	928	430

The foregoing table deals with energy values. The effect of air mass on light quality in the visible spectrum is described by Withrow (36): (The reader should not confuse the term "peak energy" in the following excerpt with "total energy", which under all air mass conditions is greater in the infrared than in the visible spectrum).

"At high solar angles on a clear day, the peak energy is in the green, but as the sun approaches the horizon and the air mass increases, the blue is attenuated more rapidly than the red and the peak shifts from the green toward the orange and finally to the red. At all times, however, the peak energy of combined sun and sky radiation is in the visible."

Effect of Altitude and Aridity

The effect of altitude on the total solar radiant energy received at ground surface largely involves the infrared side of the wave band and is mainly related to differences in water vapor as a filtering factor. In Moon's article, for example, an arid climate condition of zero water vapor and zero dust particle content at 2200 meters altitude is assumed and a reduction of ozone from 2.8 mm at sea level to 1.8 mm at 2200 meters is cited. This reduction in ozone is small to meteorologists interested in the ultraviolet radiation filtration which takes place in the total depth of air envelope through which the solar radiant energy passes, but is significant in its erythema effects and possibly in its effect on some non-viable materials. Energywise, the effect of altitude is perhaps more significant since over 50% of the solar energy reaching the earth's surface is infrared energy and it is in this band (7600 to 23,000) that water vapor interposes the main barrier. In the absence of water vapor the energy comes through to the ground surface. There is at the same time a more rapid loss of energy at night because of the lack of diffused heat retained in the air envelope as a result of filtration (i. e. absorption), and refraction.

It is generally known that with a substantial increase in altitude, the direct rays of the sun have more heating power (mainly due to more radiation on the red side), and that sunburn is

acquired more rapidly (ultraviolet radiation). This is because the blanket of ozone in the atmosphere is thinner (ultraviolet filter), and there is generally much less water vapor overhead (infrared filter). Nitrogen oxides, carbon dioxide and ozone also play a secondary role in filtering out infrared radiation, with nitrogen oxides active at 7500 to 8000 AU, ozone active at 9000 to 10,000 AU and carbon dioxide active at 13,000 to 13,900 AU and controlling between 13,400 and 13,900 AU. These air-gas blankets also are thinner at high altitudes.

As an index of changes in ultraviolet irradiation due to altitude, Moon cites a minimum perceptible erythema (MPE) value of 29.8 minutes at sea level (based on Washington, D. C.), vs. 10.1 minutes at 2200 meters altitude (based on Flagstaff, Arizona). MPE is an index of ultraviolet radiation.

The effect of either an arid climate or altitude on the quality of solar energy transmitted to the ground surface is illustrated by the Smithsonian Meteorological Tables (5) (p. 433-6), which list the percent transmission of solar radiation through the atmosphere at different wave lengths for a number of different observed values of atmospheric water vapor content. Except for some transmission losses of secondary value due to ozone at 9000 to 10,000 AU, a condition of zero water content (not shown in table), would result in a transmission baseline rate of approximately 90% in wave bands up to 13,000 AU for the air mass conditions of the observations. Beyond that, CO₂ begins to play an important role. Adjustment has been made in the tables for the filtering effects of these other atmospheric air-gases. By comparing the spread between the highest water content value and the lowest, a general understanding of the energy filtering function of increased water vapor content due to decreasing aridity or lowered altitude, or both, can be obtained.

The wave band values tabulated below are averages derived from the source tables which give energy transmission percentages at each interval of 100 AU in wave length. There is often substantial change from interval to interval within a band. This is due to the very large number of narrow water vapor absorption lines (with intervening "windows"), which occur in some

wave band ranges. There are 66 "lines" for example, between 6480 and 7000 AU, having different intensities. Thus, the faithful simulation of solar irradiation by artificial light sources under the widely varying water vapor conditions which occur from day to day and in different areas of the U. S. would entail programming of great complexity.

Wave band (angstrom units)	Percent transmission of solar radiation by the atmosphere --	
	At lowest cited water vapor content	At highest cited water vapor content
5,500 - 7,900	34	3
8,000 - 11,000	83	46
11,000 - 13,000	90	63
13,000 - 13,500	rapid decline	rapid decline
13,500 - 22,000	very low	very low

Influence of Latitude

As is well-known, latitude is important in determining length of day and season of the year. Day length is a significant factor when plants are grown in a controlled environment facility, but the adjustment of artificial irradiation to satisfy this situation is a programming function of the simplest character provided the control conditions are established. There is no design or facility evaluation factor involved in the matter of turning an entire bank of lights on and off.

Theoretically, latitude must be involved in the total energy supplied by solar irradiation in order to simulate the biological "climates" of different latitudes. The range in geographical latitude of the original 48 states is from about 26° to about 49° North Latitude. That of the 50 states is from 26° to 70°. When dominions and possessions are added it becomes somewhat greater in a southerly direction.

The Smithsonian Tables have data on this subject, both in daily and annual values (p. 420-422). Under a constant transmission coefficient, the total daily irradiation when the sun is at its most favorable longitude (90° and June 22 in the northern hemisphere), is 481 energy units at 30° North Latitude, 450 energy units at 50° and 349 energy units at 70°. As a baseline, the value at

the equator (0°) is only 372 units, compared with a peak of 447 units at the equator on March 21.

Annual energy values from solar irradiation, listed for half-years and full year, follow. A constant transmission coefficient has been selected. The equator (0°) is used as a reference.

	Solar irradiation energy values at latitude -			
	0°	30°	50°	70°
Summer half-year	76	82	67	41
Winter half-year	76	41	13	10
Total	152	123	80	51

These figures indicate that any facility concerned with simulating solar irradiation conditions based on differences in latitude would not be faced with as great a problem in irradiation capacity or programming as it would in satisfying the conditions of some other variables. The annual variation within the 48 states area is about 50%; that from the northern boundary of Alaska to the mouth of the Rio Grande River in Texas is about 150%.

Effect of Overcast

Solar energy transmission through atmospheric water vapor and other filtering gases as reviewed previously are for clear-day conditions. The Smithsonian Tables, on page 441, give the total solar irradiation energy transmission rate for eight different cloud and fog conditions under different air mass conditions. Clear-day conditions are shown as a reference base. Some energy values have been excerpted to show the filtering effect under best (cirrus) and worst (nimbostratus) cloud conditions and to show the range of variation which would be required for the faithful programming of artificial irradiation. These values deal with constant overcast conditions. The mixed clear-overcast conditions which so commonly occur in nature during the course of a day would interpose major added programming problems.

Air mass	Energy transmission rates		
	Clear	Cirrus clouds	Nimbostratus clouds
1.5	60	50	10
3.5	22	17	6

Summation

The accompanying figures reflect the many variables previously described in this section only to a very limited extent, especially because they do not show the effect of the constantly changing air mass conditions throughout the daylight hours or the changes in cloud cover which occur in nature.

Figure 1 presents a general approximation of the spectral pattern of solar irradiation at the edge of the earth's atmosphere and at ground surface under Moon's standard solar irradiation curve for air mass 2 as given in his Table III. His assumed standard conditions are: 760 mm. barometric pressure, 300 dust particles per cubic centimeter in the atmosphere, and an ozone and water vapor content of 2.8 and 20 mm. respectively at air mass 1. They more or less reflect clear day sea level conditions in the latitude of Washington, D. C.

The energy values by wave band regions at the earth's immediate source of supply (i.e., air mass 0), are about as follows:

Wave band region	Relative energy, percent
Ultraviolet (3000-3900 AU)	6
Visible spectrum (3900-7600 AU)	39
Infrared (7600-23,000 AU)	55
Total	100

To show more precisely the values and relationships between air mass 0 and 2 conditions, the wave band regions have been subdivided in Figures 2, 3 and 4. Since the wave band spectrum in Moon's Table III for air mass 2 covers a range of from 2950 to 21,400 AU, with energy values

ranging from 2.09×10^{-7} to 1.215 for air mass 2 and to 2.127 for air mass 0, it is necessary to plot the short-wave band region on multi-cycle semi-log paper and even then to further dampen the air mass 0 values by one cycle through use of a separate ordinate scale. These practices in combination have the effect of greatly dampening the visual spread between the two curves.

In summary, the general picture presented by Figure 2 is the extremely high filtering effect of the atmosphere on the ultraviolet wave band region, mainly by ozone. That presented by Figure 3, as compared with Figures 2 and 4, is the relatively limited filtering effect of the atmosphere on a clear day on wave bands in the high-energy visible spectrum region and on infrared wave bands in the 7600 and 10,400 AU region. The pronounced curtain which reaches its maximum effect at 9300 AU is an outstanding exception. Figure 4 shows the increasing width and depth of the valleys created in the air mass 2 curve by absorption bands in the 11,000 to 12,000 AU wave band region, again at 13,000 to 15,000 AU, and again at 17,000 to beyond 20,000. The terminal point is reached at 21,400 AU due to absorption although the air mass 0 table in Moon's article extends to 50,000 AU with a value of 0.004 langleys at that point.

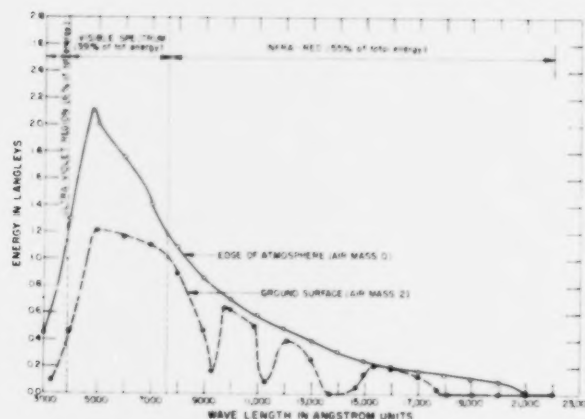


Figure 1. SOLAR IRRADIATION IN LANGLEYS FOR WAVE LENGTHS REACHING THE GROUND SURFACE AT SIGNIFICANT ENERGY LEVELS UNDER AIR MASS 0 AND AIR MASS 2 CONDITIONS.

(After Parry Moon - Tables 1 and 2).

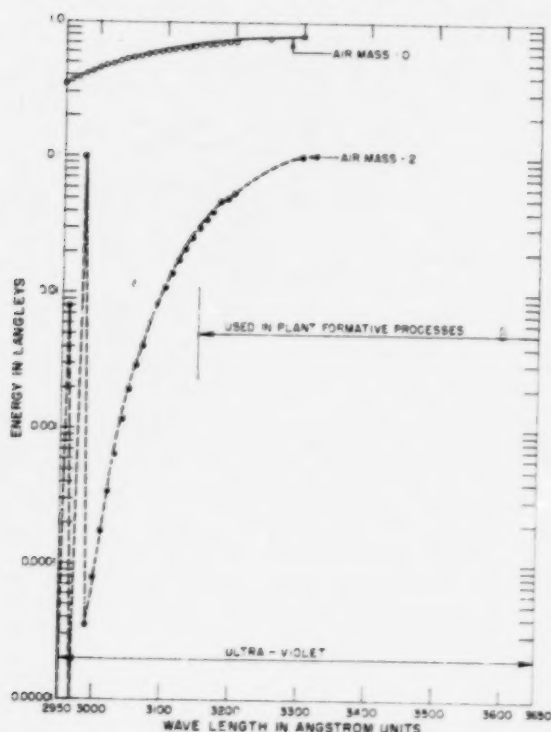


Figure 2. SOLAR IRRADIATION IN WAVE BAND REGION 2950 TO 3300 ANGSTROM UNITS AT AIR MASS 0 AND AT AN AIR MASS 2 STANDARD NORM CONDITION. (After Parry Moon).

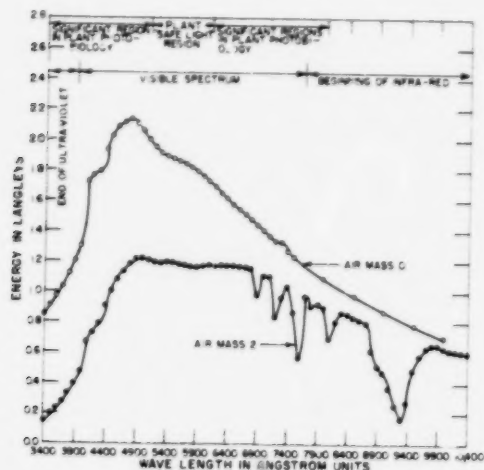


Figure 3. SOLAR IRRADIATION IN WAVE BAND REGION 3400 TO 10,400 ANGSTROM UNITS AT AIR MASS 0 AND AT AIR MASS 2 STANDARD NORM CONDITION. (After Parry Moon).

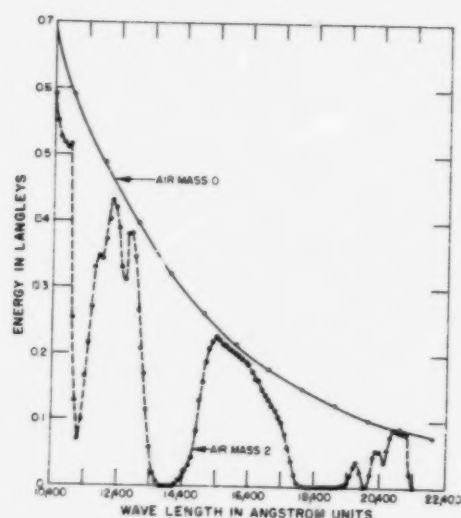


Figure 4. SOLAR IRRADIATION IN WAVE BAND REGION 10,400 TO 21,400 ANGSTROM UNITS AT AIR MASS 0 AND AT AN AIR MASS 2 STANDARD NORM CONDITION. (After Parry Moon).

Solar Irradiation Requirements of Plants

Solar irradiation is utilized directly or indirectly by plants in two principal ways: (1) for thermal energy and (2) as an energy supply for photochemical activity as an element of photobiological processes.

Thermal Requirements

The direct and indirect thermal requirements of plants are obtained both from radiant energy wave band regions not utilized by photo processes (mainly infrared), and from irradiation exceeding photochemical requirements in the photo wave band regions. Such thermal requirements, however, are not of critical interest in this study since any heat source should serve all or most of these needs, and that received from simulated solar irradiation does not need to be wave band-specific. This is in sharp contrast to the wave band-specific characteristics of plant pigment excitation in the photobiological processes. These processes, of course, also utilize thermal energy.

Photobiologic Energy Responses and Requirements

Practically all plants require energy for two distinct but interrelated photochemical reactions. One is photosynthesis; the other might be termed non-chlorophyll photochemical pigment activity.

The primary energy source for chlorophyll pigments in photosynthesis is irradiation in the wave band ranges of 4000 to 5100 AU (violet-blue), and 6100 to 7000 AU (orange-red). Secondary energy sources for photosynthesis may consist of irradiation in these and other wave band regions which may be converted by non-chlorophyll pigments into energy utilized by alpha chlorophyll, the essential chlorophyll in photosynthesis.

The non-chlorophyll photochemical pigment reactions are mainly of a hormone-response type in the control of plant development. One important area of plant response of this type is known as the "near-red far-red effect." According to Borthwick⁽¹⁹⁾, the near-red effect depends on the yellow and visible red wave length region 5500 to 7000 AU, with a maximum of about 6500 (red). The far-red reversal effect uses irradiated energy in the region 7000 to 7500 AU, with a maximum near 7350 AU. Van Der Veen⁽³³⁾ extends this region to 8000 AU, which carries it into the infrared. Other photochemical responses take place at 4000 to 5100 AU where irradiation is absorbed by yellow pigments which induce various important reactions such as phototropism, streaming of protoplasm and movement of chloroplasts. The wave band region 3150 to 4000 AU, known as the "ultraviolet A" region, also has a formative effect on plants. They become shorter and thicker. The adjoining shorter wave length "ultraviolet wave band B" region is detrimental to most plants, while irradiation below 2800 AU rapidly kills them. Radiation below 2975 AU is not encountered in significant quantity at ground level under most conditions.

Plant scientists do not yet have full knowledge or even complete identification of all of the plant pigments which enter into photochemical processes. The known pigments other than the chlorophylls include carotene, lactoflavin, phycoerythrin, fucocanthin, anthocyanin, phycocyanin and the xanthophylls. Some are

found in greatest concentrations in red, brown, blue and purple colored plants, including red, brown and blue algae.

Although plants have definite spectral quality requirements for the irradiation they receive, it does not follow that they require for proper development the maximum intensity supplied by solar irradiation in each wave band region. If this were so, they could not develop under the varied diurnal, seasonal and weather conditions in nature. This is rationalized by Withrow⁽³⁶⁾ as follows:

"Responsewise, plants see the logarithm of the intensity. This holds for the plants we have studied at all values above 0.001% of noon sunlight.

"What the plant sees is a very rapid rise in light intensity at sunrise (i.e., from 10 to 100 ft.-c. in 20 min.), which within a few minutes reaches saturating values and then, as far as the plant is concerned, the intensity is above saturation until sundown when within a matter of minutes the intensity falls to zero.

"In terms of carbohydrate supply, photosynthesis is not significantly active at intensities below about 100 ft.-c., whereas the regulatory photochemical reactions are excited to significant levels by many thousand-fold lower values. The intensities of moonlight are well within the significant range of plant photomorphogenic responses." (Chapter authored by Withrow on Kinetic Analysis of Photoperiodism).

This entire subject of irradiation intensity and spectral quality is basic to the review of different types and characteristics of lamps for simulated solar irradiation and the irradiation facilities in the various plant growth rooms visited.

Figure 5 (after Van Der Veen⁽³³⁾ and Withrow⁽³⁶⁾), provides perspective on the overall spectral quality requirements of plants. An excellent reference for further information on plant photobiology is presented by Van Der Veen⁽³³⁾.

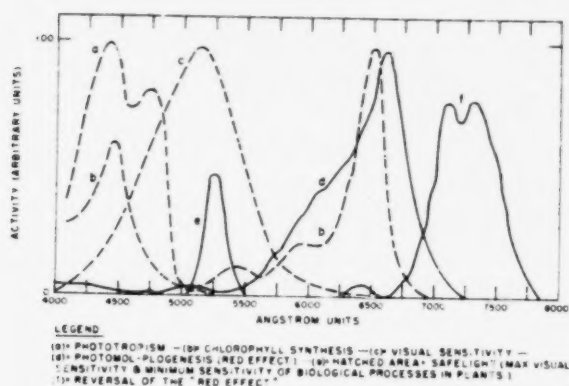


Figure 5. SPECTRAL ACTIVITY OF SOME PLANT PHOTOBIOLOGICAL PROCESSES.

Solar Irradiation Simulation With Lamps

The more or less normal growth of possibly all species of terrestrial plants in plant growth rooms has been demonstrated empirically so often with conventional lamps that there is little point in making an exhaustive theoretical analysis of intensity and spectral light characteristics of special types and combinations of lamps in this study from the standpoint of faithfully simulating solar irradiation at ground surfaces. The present study is a survey of existing facilities and an appraisal of how well they serve their purpose. As will be brought out in a later section of this report, conventional lamps are used in plant growth rooms even though they do not faithfully simulate solar irradiation.

This is understandable from the plant photobiologic processes presented in the preceding section and by the fact that the lamps in use do not depart so radically from solar irradiation conditions that plants are unable to develop in a so-called normal manner. Equally important, the photo intensity and thermal energy supply are also ample.

The extent and degree to which the Sanitary Engineering Center's requirements for simulated solar irradiation may or may not depart from those of the facilities surveyed is a subject for another study. However, a summarization of the characteristics of some lamps may be in order.

The two lamps considered conventional for ordinary use and plant growth room use are the common types of incandescent filament and fluorescent lamps. Detailed characteristics of these and of most special purpose lamps, except carbon-arc lamps, are thoroughly described in General Electric Lamp Bulletin LD-1* (January 1956); a few new models introduced since that date are not covered. This bulletin deals with all types of incandescent filament, fluorescent, and specialized mercury lamps.

Outstanding characteristics of the conventional incandescent filament lamp are its low efficiency in converting energy into visible light, its high infrared output, and low ultraviolet output. Its low efficiency makes it much more expensive to operate for visible light production than the fluorescent lamp. In a plant growth room the high heat output of the filament lamp increases construction cost and adds further to operating cost due to heat dissipation problems.

Only 10.0 to 11.1% of the total input energy is emitted beyond the bulb as visible light by standard types of 100 w. to 300 w. filament lamps (Table on page 12 of the Bulletin). About 80% of the total input energy is emitted as infrared radiation. Practically all of the remaining 10% is lost as convected or conducted heat from the bulb surface since the ultraviolet radiation is negligible.

A spectral energy distribution table on page 40 of the Bulletin gives the following comparative values for 40 w. incandescent and cool white fluorescent lamps. (The cool white is perhaps the most commonly used fluorescent lamp in plant growth rooms.)

Lamp type	Ultra-violet radiation 2900-4000 AU	Watts emitted			
		Visible radiation			
		4000-5000 AU	5000-6000 AU	6000-7600 AU	Total visible
40 w. filament	0.027	0.021	0.59	1.85	2.65
40 w. fluorescent-cool white	0.300	2.46	3.48	2.11	8.05

*Mention of commercial products in this report is not to be construed as an endorsement of them by the Public Health Service.

These data indicate that the filament lamp emits about 40% as much radiant energy in the spectral regions of maximum plant photochemical energy utilization (4000 to 5000 AU and 6000 to 7600 AU) as the cool white fluorescent lamp of the same input wattage.

Comparison of the spectral energy distribution of fluorescent lamps with that of solar irradiation reaching the ground surface under an assumed pattern (GE Bulletin, pp. 38-9) shows that the daylight fluorescent lamp conforms closely to the solar irradiation pattern in most of the higher energy requirement regions of plants (zones of maximum photosynthetic energy demand), but is sharply lower on the ultraviolet and infrared sides. This weakness on the red side lessens in the visible red zone of maximum photosynthetic activity. However, when supplementary filament lamps are provided in the lamp bank they furnish some support in this zone as well as in the near infrared zone which influences certain plant photochemical processes.

No data are presented in the GE Bulletin on the over-all efficiencies of fluorescent lamps or on their comparative efficiencies with filament lamps in terms of "what the plant sees." A rough approximation can be made, however, from the preceding table. The procedure in the following table is open to question in certain respects but as an approximation indicates that the fluorescent lamp is nearly three times as efficient.

	Watts	
	Fluorescent	Filament
Total visible watts	8.05	2.65
Plus ultraviolet (2900-4000 AU)	.30	.03
Subtotal	8.35	2.68
Less energy in the 5000-6000 AU zone	-3.48	-0.59
Net available	4.87	2.09

The special purpose lamps described in the GE Bulletin include lamps with special characteristics on the ultraviolet and infrared sides of the spectrum. They do not include lamps which cover the full spectrum range more adequately than conventional filament and fluorescent lamps, alone or in combination.

The Strong Electric Co., 87 Park Ave., Toledo 1, Ohio, has a specialized interest in carbon-arc lamps and besides other lamps for use in photography and motion picture projection offers the "Strong Solar Radiation Simulator."

The carbon-arc lamp because of its very high operating temperature, compares more closely to solar irradiation in spectral light pattern at the edge of the earth's atmosphere or beyond, than that of any other commercially available lamp. For this reason it is of special interest to those concerned with space research. By the same token, it simulates solar irradiation under ground level conditions far less faithfully, even under clear-day conditions. It is especially high on the ultraviolet side even though it does not surpass air mass 0 values (i. e., edge-of-atmosphere), in this or other wave-band regions.

The Strong Jetard lamp is capable of operating only 20 minutes, then it is necessary to retrim with new carbons, which takes 15 to 20 seconds. Plants probably are not adversely affected by this but operating costs are. The manufacturer is considering an automatic loader which would permit the lamp to operate 4 to 5 hrs. without reloading. This lamp, incidentally, is rated at 155 Amps. at 75 v. or 11.5 kw.

The carbon-arc lamp seen at the A.R.S. Plant Industry Station at Beltsville, Md. (see Appendix) operates automatically up to eight hrs., even though it is a model 25 or more years old. The reasons behind this "state of the art" situation are not known. The lamp at Beltsville is rated at 75 Amp. at 60 v. or 4.5 kw.

For further description of the applicability of other special types of lamps for plant growth rooms, see Van Der Veen's book listed in the Bibliography.

Other Considerations

Evaluation baselines considered so far have been concerned with the simulated solar irradiation variable. Four other specified variables remain -- temperature, relative humidity, simulated altitude, and wind. Water wave-making facilities also have been considered to a very limited extent.

It is doubtful if much baseline data are required here as a prerequisite to consideration of survey information gathered on these variables in existing and projected facilities. Such data might be supplied in a future study of the Center's development and use of a controlled environment facility adapted to its needs. One reason for this lack of need for baseline data is the fact that the survey of water wave-making facilities has been too limited and superficial to require development of a theoretical background for evaluation of these facilities.

Brief consideration might be given to the relative humidity variable under simulated natural conditions of a controlled environment facility. One aspect is the interrelationship between temperature and relative humidity as a result of which these two variables can only be considered in combination.

It is well-known that the daily change in ambient temperature in a temperate climate can range from as little as 0° to perhaps 60° F or even more; variations of 20° to 30° may be considered more or less normal.

These daily temperature swings are accompanied by related variations in relative humidity. In a coastal climate the maximum relative humidity when the daily temperature is lowest may be 95%. Under constant absolute humidity conditions, a standard barometric pressure of 760 mm, and a daily temperature swing of 20° F (such as from 60° to 80°), the relative humidity swing is from 95% to 50%. In a drier climate having a 30° F temperature swing (such as from 40° to 70°), and a maximum relative humidity of, say, 60%, the relative humidity swing is from 60% to 21%.

As an index of regional variation, average monthly relative humidity records at U.S. weather stations for September 1960 were reviewed. (U.S. Weather Bureau National Summary of Climatological Data). In the 48 states area the range was from 28% (Elko, Nevada), to 86% (Daytona Beach, Florida). Extended to include Alaska, the highest value was 96% (Barter Island).

Another aspect is the effect of terrestrial plant

life and of bodies of water on the humidity of a closed-space controlled environment facility. At one plant growth room visited, for example, it was stated that under a constant temperature condition the relative humidity varied in the order of 30 percentage points in a 24-hr. period due to changes in plant and soil transepiration rates.

In evaluating the surveyed facilities these two factors in combination pose questions as to whether relative humidity control is needed at all, whether it should be supplemental or complete, whether it should be precise or crude in sensitivity, and whether the control equipment should be of a type intended for continuous or for intermittent operation. Similar questions arise pertaining to temperature control.

These questions illustrate three different philosophies of approach to the over-all subject of environmental controls in a facility, two of which were encountered frequently in this survey.

One approach is that of the experimentalist who desires rigid standardization and utmost sensitivity of control of environmental conditions, although he may wish to vary them from time to time.

The second approach is that of the plant scientist interested in growing plants under development conditions more or less comparable to those in nature during the growing season in order to observe them for some special purpose but who is indifferent to simulating the natural environment *per se*. For example, on the one hand, such plant scientists tend to be unconcerned with precisely standardizing temperature and relative humidity conditions although they may wish to avoid extremes detrimental to plant development; to this extent they follow nature's pattern with its daily swings. On the other hand, they are indifferent to programming diurnal irradiation levels, raising them to maximum intensity values or replicating spectral quality in an effort to simulate nature because plant development suitable for their experimental purposes can be obtained under steady daytime light intensities or other unnatural conditions which yet satisfy plant requirements.

A third approach would place models in a

facility to observe "normal" behavior under a complex of environmental variables as they occur in nature. An oxidation pond would be one example of such a model. In this case, a study of the "normal" behavior of an oxidation pond might require the algae in it to behave "normally" not merely in development rate but also in lateral and vertical movement in the aquatic medium. Accomplishment of such an objective would require among other things, diurnal light programming (i. e., an approach to the "faithful" simulation of nature).

Climatologic Data

Evaluation of the concept of exposing test models in a facility to the full range of simulated climatologic conditions of the United States requires among other things, inquiry as to whether the basic data are available for programming these conditions. For present purposes "programming" means simulating the values and changes of values as they occur in nature, irrespective of what unit of time is deemed appropriate for such programming.

It is common knowledge that the U.S. Weather Bureau collects and publishes climatologic data for a large number of weather stations in the United States and there is little point in fully describing the Bureau's program. Not all details are equally known, however, and a few are mentioned as reminders or as new information to some.

Items of particular interest pertain not only to some of the lesser known data collected, but the extent of collection and the periods of years covered by pertinent summaries.

The Weather Bureau has about 300 first-order stations in which data are collected more completely and more frequently than at the far greater number of lower-order stations. At these primary stations, hourly observations are made of temperature, relative humidity, precipitation, sky cover ceiling-visibility, and wind speed. The Bureau has recently completed a 5-Year Summary (11) of these hourly observations and is presumably undertaking preparation of 10-Year Summaries. Among other things, these summaries give percentage frequency tables for observed values by time of day and, in one case, relative to another observed variable.

The National Summary of Climatological Data (12), issued monthly and annually, gives

not only a condensation of the more familiar climatologic items, but also special data. The special data includes general summaries of storm, river and flood conditions and detailed summaries of rawinsonde, solar radiation and ozone data. This information is presented in text, table and chart form. Of particular interest are the data on solar radiation and ozone.

As of November 17, 1960, the Solar Radiation Network consisted of 86 stations, of which 76 were in 41 states in the 48-state area, 5 were in Alaska and 5 were in Pacific islands. Seventy-nine reported radiation observations for horizontal surfaces and 7 for normal incidence. About 60% of the total stations reported hourly values and about 40% daily values.

The normal incidence stations are located in Arizona, Guam, Hawaii, Massachusetts, Nebraska, New Mexico and Wisconsin. Solar radiation intensities in langley's per minute are reported by days of the month for 9 air mass conditions (corresponding to time of day). In September 1960, average solar intensities under air mass condition 1 (zenith) in 6 of these stations (1 of the 7 was inoperative) varied from 1.02 langley's per minute at Omaha, Nebraska, to 1.65 at Mauna Lao, Hawaii. The peak single day value at any station was 1.68 at Mauna Lao or 86% of the solar constant. This station is at elevation 11,150 ft. msl. The lowest value at any station under clear-day conditions was 1.07 or 55% of the solar constant (Omaha, Nebraska).

At the much larger number of "horizontal surface" stations solar radiation values were reported daily in total langley's.

There were 5 stations reporting the total amount of ozone in the atmosphere each day in September 1960 under air mass 1 conditions. The location, elevation and range of daily values are given in the following table. These values compare with Moon's "Standard Curve" value of 2.8 mm. (8).

Station	Elevation, ft. msl	Ozone content, mm.	
		Min.	Max.
Mauna Loa, Hawaii	11,150	2.67	2.84
Caribou, Maine	640	2.75	3.85
Bismark, North Dakota	1,670	2.62	3.10
Ft. Worth, Texas	555	2.72	2.99
Green Bay, Wisconsin	689	2.44	3.07

OBSERVATIONS

Presented in Tables 1, 2, 3, and 4 are observations on the locations, types, sizes, controlled variables design ranges, and operating and construction costs of various facilities. An effort is made to draw conclusions on patterns of controlled variables in a facility, the mechanical engineering aspects of humidity and temperature control, simulation of solar irradiation, characteristics of a potential aquatic facility, and operating and construction costs. Consideration is given to simulated altitude and wind variables.

Facilities Visited

Much of the information in this survey was obtained through visits to various facilities, some of which are briefly described below. Detailed accounts of these visits are given in the Appendix.

The Climatron at Missouri Botanical Garden, St. Louis, Missouri - The Climatron is a Plexiglas hemisphere for growing tropical vegetation. It was built at a cost of \$700,000 and has a temperature range of about 10°F; it depends primarily on solar irradiation through the Plexiglas dome. The purposes of the Climatron are public education, recreation and, to some extent, research.

Technical Development Laboratories, Communicable Disease Center, U. S. Public Health Service, Savannah, Georgia - The laboratory at Oatland Island Station, built in 1955, has an 8-ft. cubical controlled humidity chamber for calibrating and testing bacteria-in-air samples. Two new controlled environment facilities are being developed; one is under construction at Oatland Island, and a larger one for CDC headquarters in Atlanta is in the planning stage. Both will be used to study bacterial movement, removal, and survival in the air of interior spaces such as hospital rooms, and for more basic studies under highly standardized conditions. The controlled variables are temperature, relative

humidity, and air movement, and all three facilities have been designed to obtain a very high order of sensitivity and precision. The overall construction cost of the larger facility planned for CDC at Atlanta is estimated at \$250,000.

Ray W. Herrick Laboratories for Research in Refrigeration and Climate Control, Purdue University, Lafayette, Indiana - This is a non-profit contract laboratory whose main objectives are in the field of education. The variables under investigation include temperature, air composition, air movement, noise, and light. The Herrick Laboratory building, constructed at a cost of approximately \$1,000,000, is the most sophisticated and expensive of all the climate control facilities visited and is known to be surpassed in temperature range only by the ERDL test chamber at Ft. Belvoir, Virginia.

Agricultural Research Center, Monsanto Chemical Company, St. Louis, Missouri - The two types of controlled environment facilities here are insectary rooms with temperature and relative humidity control but no other variables, and "growth" rooms with temperature, relative humidity, artificial light controls, and air movement. The primary purpose of these rooms is to grow terrestrial plant life under artificial conditions approximating those in nature to test the effects of agricultural and mold-control chemicals on these plants. The cost of constructing this controlled environment facility was approximately \$50,000.

Southwest Water Conservation Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Tempe, Arizona - This consists of a single growth room for studying the effect of environmental factors on the uptake, translocation, and transpiration of water by plants. The environmental controls and their ranges are: Temperature - 4°C to 40°C (39°F to 104°F); irradiation - 0 to 3500 ft. candles; relative humidity - 5% to 95%. This entire facility was constructed under the supervision of GSA. It is estimated that the growth room construction cost was about \$60,000.

Table 1. CONTROLLED ENVIRONMENT FACILITIES

Facility location and type	Controlled variables*
1. Agricultural Research Service (A.R.S.), Watkinsville, Ga. (a) Plant growth (b) Plant growth	Irradiation: filament; temperature Irradiation: filament, 1.55 langley's max. rate; temp: 41-122°F; relative humidity: 10-90%
2. Purdue University (a) Altitude chamber (b) Climate-low temp. capability	Altitude: 90,000 ft. Temp: -30-130°; rel. humid: 25-90%; air change time: 0.25 min.
3. Monsanto Chemical, St. Louis (a) Climate-insectaries (b) Plant growth-4 rooms	Temperature; relative humidity Irradiation: fluorescent-filament, 3000 ft-c max. rate; temp: 50-120; rel. humid: 50-98%; air change time: 0.5 min.
4. Missouri Botanical Garden, St. Louis Plant growth-Climatron	Irradiation: filament-spot, low max. rate; temp: 60-90; rel. humid: 60-90%; air change time: 2 min.
5. A.R.S., Tempe-Phoenix, Arizona (a) Plant growth (b) Total climate (contemplated)	Irradiation: fluorescent-filament, 3500 ft-c max. rate; temp: 39-104; rel. humid: 5-95%; air change time: 6 min. Irradiation: temperature; relative humidity; wind; altitude
6. Solar Energy Lab, Tucson, Arizona Basic data	Irradiation; temperature
7. Emory University, Atlanta, Ga. Plant growth	Irradiation: filament, 12,000 ft-c max. rate; temp: 40-100; rel. humid: 15-90%; air movement
8. Com. Disease Center, Savannah, Ga. Bacteria-indoor air	Temperature; relative humidity; air movement
9. Com. Disease Center, Atlanta, Ga. Bacteria-indoor air	Temp: 30-100; rel. humid: 25-95%; air change time: 0.5-25 min.
10. Georgia Tech., Atlanta, Ga. (a) Wind tunnel-low turbulence (b) Wind tunnel-aerodynamic	Turb. factor 0.00062; velocity 70 fps Velocity 160 mph
11. Engr. Res. & Dev. Lab, Ft. Belvoir, Va. (a) Climate-low temp. capability (b) Climate-tropical (c) Outer space	Temp: -85-165; rel. humid: 20-100%; altitude: 35,000 ft. Temp: 70-100; rel. humid: 50-100%
12. A.R.S., Beltsville, Md. (a) Plant growth (b) Plant growth-2 rooms	Irradiation; temperature; relative humidity; altitude Irradiation: carbon arc-filament, 3300 ft-c max. rate; temperature; rel. humid: captive; air movement Irradiation: fluorescent-filament, 2000 ft-c max. rate; temp: 60-80; rel. humid: captive; air change time: 0.7 min.
13. Natl. Inst. of Health, Bethesda, Md. (a) Altitude-low temp. (orig. facility) (b) Altitude (modified facility) (c) Altitude (contemplated facility)	Temp: to -80; altitude: 50,000 ft. Altitude: 16,000 ft; conventional air-conditioning Conventional air-conditioning; altitude: 50,000 ft. (pre-fab. commercial)
14. U.S. Navy, Carderock, Md. Water wave-maker	Water-waves: waves 0 to 24" high, 3' to 20' from crest to crest
15. Coastal Engrg. Lab-Univ. of Florida Water wave and wind	Wind; water-waves: waves 0 to 20" high, period 1.5 sec. up
Pre-fabricated commercial units	
16. Percival Programmed Plant Growth Lab. Plant growth	Irradiation: fluorescent-filament, 4600 ft-c max. rate; temp: 45-95; rel. humid: 75-100%; air change time: 5 min.
17. Labline Model 860 Plant growth (also 2 other models)	Irradiation: fluorescent-filament, 2000 ft-c max. rate; temp: 25-90; rel. humid: 25-95%
18. Tenney Walk-in Space Chambers Climate-alt. (also other models)	Irradiation: max. rate 140 w. per sq. ft; temp: 150-2000; rel. humid: as desired; altitude: to 1500 ft; rain 24" per hr.
19. Guardite Chambers Climate-alt. (also other models)	Irradiation; temperature; relative humidity; altitude; air movement. (Units are designed to meet needs).
20. Vacudyne Chambers Climate-alt. (also other models)	Irradiation; temperature; relative humidity; altitude; air movement. (Units are designed to meet needs).

* The range of the variable is given where known.

Table 2. NOTES ON CONTROLLED ENVIRONMENT FACILITIES AT UNIVERSITIES

1. University of Wisconsin

Projected facility under Dr. H. A. Senn aided by \$1.5 million construction grant from National Science Foundation for a biotron with rooms within facility to study environmental influences on plants, small animals and perhaps large animals and man. Environmental controls will include temperature, moisture, air motion, light, sound and magnetic fields.

2. University of Illinois

Physical Environment Unit of Graduate College has 2 large rooms for climate control and an altitude chamber. Human Environment Research Laboratory of Department of Physiology has 4 climate rooms with treadmills with temperature range of -50° F to 180° F and relative humidity range of 5-100%; also climatically controlled rooms to study problems of comparative physiology with aquatic or terrestrial organisms. Climate chamber being constructed at College of Veterinary Medicine with temperature and relative humidity for zoonoses studies. Department of Zoology has small climate rooms to study energy balance and behavior of birds and small animals. Department of Animal Science has climate chamber to study metabolic and nutritional problems with small animals such as rats and chickens. All of these are at the Urbana campus.

The Chicago campus has climatically controlled altitude chambers for aviation physiology studies at Aero Medical and Physical Environment Laboratory. Research and Educational Hospital has climate rooms where normal and ill patients can be studied while under complete metabolic control.

3. Northwestern University

Research on climatic influences on birds, microclimatological studies of caves and soil and rhythmicity in organisms under regulated conditions are carried out. Facilities include twenty-two 2-ft. cubical chambers in which "most of the known meteorological elements can be controlled."

4. Indiana University

Department of Anatomy and Physiology at Bloomington campus has climate chamber with treadmill for human physiology studies in hot climates. Department of Physiology at Indianapolis campus has human environmental chamber to study physiology of adjustment and acclimation to cold.

5. University of Iowa

Department of Physiology has climate chambers for animal and human physiology studies with air-conditioning, controlled hours of simulated daylight and low-temperature controls.

6. University of Chicago

Laboratory of Climatology on a "50,000-acre" farm has an instrument laboratory to develop instruments for micro-meteorological investigation. Principal research in climatology is in heat and water balance problems. Located at Centerton, N.J., under Thorntwaite who is now associated with University of Chicago.

7. University of Minnesota

Several small phytotrons located on campus. Laboratory of Physiological Hygiene has human climate chambers with treadmills.

8. University of Ohio

Controlled environment facilities not specifically described but there is an "Institute for Polar Studies" and laboratories for research in atmospheric physics, comparative and physiological psychology, nutrition, aviation physiology and environmental physiology which involve controlled environment facilities.

9. Michigan State University

Controlled environment facilities include poultry houses with environmental controls and climate chambers for small animals.

Table 3. SUPPLEMENTARY LIST OF CONTROLLED ENVIRONMENT FACILITIES

Name and location	General description and remarks
1. Beach Erosion Board, Corps of Engineers, Washington, D. C.	Water-wave machine - wobble plate type
2. Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss.	Water-wave machine
3. Massachusetts Institute of Technology, Boston, Mass.	Water-wave machine
4. Taft Sanitary Engineering Center, Cincinnati, Ohio	Plant growth room - air pollution
5. Purdue University, Lafayette, Ind.	Plant growth rooms - temp. & irradiation
6. Oklahoma Agricultural Experiment Sta., Stillwater, Okla.	Controlled environment facilities for evaporation studies
7. Univ. of Missouri, Columbia, Mo. (Ag. Exp. Sta.)	Controlled environment dairy barn - psychoenergetic studies
8. N. Y. Univ., Uptown Campus, Aeronautical Div. (Dr. Gordon Strom)	Low-turbulence wind tunnel - air pollution
9. Univ. of Chicago, Chicago, Ill.	Hydrodynamic facility
10. Johns Hopkins University (Dr. George Benton), Baltimore, Md.	Hydrodynamic facility
11. Woods Hole, Mass. (Dr. Bon Arx)	Hydrodynamic facility
12. Stanford Univ., Hopkins Marine Sta., Calif. (contemplated facility)	Large algal growth chamber of some type
13. Corps of Engineers, Willamette, Ill.	Ice and permafrost facility
14. U.S. Air Force, Wright-Patterson Air Force Base, Ohio	Many - mainly related to altitude
15. U.S. Signal Corps, Red Bank or Ft. Monmouth, N. J.	Climate
16. U.S. Quartermaster Corps, Natick, Mass.	Climate - materials & personnel exposure
17. Armstrong Cork Co., Lancaster, Penna.	New comprehensive facility
18. U.S. Air Force, Eglin Field, Fla.	Low-temp. plus outdoor air-blast machine
19. Philips Lamp Co., Eindhoven, Netherlands	Small plant growth chamber-light studies

Table 4. COST INFORMATION ON CONTROLLED ENVIRONMENT FACILITIES

Facility No. (Table 1)	Type	Area (ft ²)	Volume (ft ³)	Construction Cost			Energy	Operating Costs	
				Total*	Unit Area	Unit Volume		Other	Combined
1 (a)	Plant growth	36	180	\$ 3	\$ 83.50	\$ 16.60			
2 (b)	Plant growth	218	1520	50	229	33	\$ 30/day	\$ 9,800/yr.	\$20,600/yr.
2 (a)	Altitude	24	96	60	2500	623			
3 (b)	Climate-low temp.	1000	7000	700	700	100	872/mo.	11,000/yr.	21,464/yr.
4 (b)	Plant growth - 4 rooms	240	1680	40	165	24	357/mo.	3,000/yr.	7,284/yr.
4	Plant growth-Climatron	2x10 ⁴	1x10 ⁶	700	34	0.70	106/mo.		
5 (a)	Plant growth	180	1620	60	333	37	105/mo.		
5 (b)	Total climate control	Not known		2000					
6	Solar energy lab.								
7	Plant growth	15.1	54.5	10	670	18	85/mo.	360/yr.	330/yr.
9	Bacteria-indoor air	2400	48000	250	104	5.20	Under design -	Motors abt. 150 HP	
10 (a)	Wind tunnel-low-turb.	12	240	70	5.85	292			10/hr.
10 (b)	Wind tunnel-aerodynam.	9'd.	-						50-75/hr.
11 (a)	Climate-low-temp.	492	6100						
11 (b)	Climate-tropical	450	5800						
11 (c)	Space research	Not known		6000					
12 (a)	Plant growth	180							
12 (b)	Plant growth - 2 rooms	162	1300						
		162	2268	12	74	5.30	129/mo.		
13 (a)	Altitude-low temp.	57	1230						
13 (b)	Altitude	57	1230						
13 (c)	Altitude	63	882	29	468	33.50	(7.5 HP motor)		
14	Water wave	Not Applicable							
15	Water wave & wind	Not Applicable						(Motors - water 40 HP, wind 20 HP)	
		Pre-Fabricated Commercial Units							
16	Plant growth	43	322	5.7	133	18	61/mo.		
17	Plant growth	60	420	Not known			64/mo.		
18	Climate-altitude	As desired							
19	Climate-altitude	As desired							
20	Climate-altitude	As desired							

*Thousands of dollars.

Department of Biology, Emory University, Atlanta, Georgia - In a small plant growth room in the Biology Building of the University studies are conducted on controlled variables including artificial light irradiation, temperature, and relative humidity. The cost of constructing these facilities is estimated at \$10,000.

Agricultural Research Service, Plant Industry Station, U. S. Department of Agriculture, Beltsville, Maryland - This facility has a number of plant growth rooms, three of which were of special interest. All three had the same temperature controls and artificial irradiation and none had controlled humidity. The facilities at this Station, where plant growth rooms have been in operation for some 25 years, appeared to be much simpler than some of the others visited. The construction costs were estimated at approximately \$12,000 per room.

Commercially produced prefabricated controlled environment facilities - Two main types manufactured are: altitude chambers and plant growth rooms. Five companies are known to produce these facilities.

Costs

Operating Costs

The information obtainable on operating costs of controlled environment facilities was disappointingly little. The facilities visited were often minor elements of much larger laboratory and office facilities, ranging from one or two buildings to many buildings served by central power plants. Others were too new to have reliable cost data. In still others, budgets and cost accounting are so categorized that direct operating costs of the controlled environment facility are not separated from other operating costs.

The situation in one new facility illustrates in principle the problem of reliably predicting operating costs including projection of past experience to cover future conditions. The Purdue University facility is new and valid cost experience has not yet been obtained. Its climate room has been designed for a wide temperature range (-30°F to 130°F). As a result of this and other design features, the installed electric motor horsepower is high for the size of facility (400 HP for 7000 ft.³). Depending on the conditions required for a particular study, the energy actu-

ally used might range from 50 HP to the peak value of 400 HP.

Some reasonably valid information on operating costs has been obtained either from facilities visited or by developing hypothetical schedules of energy consumption. In contract facilities operating costs can be approximated by the rental fee schedule although it is likely that these schedules may include certain overhead and capital amortization charges as well as direct operating expenses.

Some operating costs and estimates are summarized in Table 4. Most "other" costs are incomplete. It is possible to estimate operating energy costs more precisely for plant growth facilities than for others. The daily number of hours the lamps are turned on is known within fairly close limits, the facility operates continuously throughout the year and the refrigeration load is relatively constant since it is determined primarily by heat emitted from the lamp banks rather than from ambient conditions. Even with facilities using lamp irradiation, however, energy consumption can vary widely in relation to space served. This range is primarily due to design factors (i. e. the light intensity employed and the type of lamp used -- fluorescent vs. filament).

"Other" operating costs were most fully supplied for the A.R.S. facility at Watkinsville, Georgia and include personal services, a mechanical service contract, and lamp replacement costs. These total \$9,800 per year for a high lamp energy plant room of 218 square feet. Except for lamp replacement costs of \$1200 per year, these operating costs should not vary for other similar plant growth space ranging from 100 to perhaps 400 square feet.

The energy operating cost, however, seems high and leads to suspicion that the figure reported does not distinguish between energy costs for the plant growth room alone and those of the entire laboratory-office facility. To the extent that it is valid, the high energy cost is attributed to the use of high-intensity lighting with filament lamps, which are inefficient as a plant photobiological light source, and the high refrigeration load imposed by the large total heat emissions. The latter is reduced to some extent by the circulating water bath.

The probable energy operating cost of a plant growth room facility such as that at Watkinsville, Georgia, if fluorescent lamps were used supplemented by filament lamps, can be projected by

drawing on data for the A.R.S. Tempe-Phoenix facility where this lamp pattern is employed.

Calculated energy cost-Tempe-Phoenix (3500 ft.-c.)	\$105/mo.
Conversion for difference in area (218/180 or 1.21)	\$127/mo.
Cost if 7000 ft.-c. were used	\$254/mo.
Reported cost at Watkinsville, Ga. @ \$30/op. day	\$900/mo.
Reconstructed operating cost for Watkinsville, Ga.	
"Other" operating costs (difference in lamp replacement costs ignored).	\$9,800 p.a.
Energy operating costs (7000 ft.-c.)	\$3,048 p.a.
Total	\$12,848 p.a.

Construction Costs

Information on construction or capital costs of facilities is more valid than that obtained directly at the source for operating costs, although it is not complete for the facilities visited. The range of cost for the existing facilities is from \$3000 for Facility No. 2 at A.R.S., Watkinsville, (Line Item 1 (a) in Table 4), to \$700,000 (Climatron at Missouri Botanical Garden and the facility at Purdue University). If projected or contemplated facilities are added the capital cost range is from \$3000 to \$6 million. For existing facilities, where information on area and volume of space is at hand, the range in capital cost for the plant growth room type of facility is from a low of \$34 per square foot for the Climatron at St. Louis to a high of \$670 per square foot for the facility at Emory University. If low temperature "climate" facilities are included the high value is extended to \$700 per square foot (Purdue University). Where simulated altitude is involved, the high value increases to \$2500 per square foot for the very small chamber at Purdue University but reduces to \$468 per square foot for the larger altitude chamber contemplated at NIH. The highest unit cost of any facility is that of the low-turbulence wind tunnel at Georgia Tech (\$5850 per square foot based on cross-sectional area).

Unit volume cost for plant growth rooms ranged from \$0.70 per cubic foot for the St. Louis Climatron to \$37 per cubic foot at A.R.S. Tempe-Phoenix. The cost of two altitude chambers was \$623 and \$33.50 per cubic foot. That of the low-turbulence wind tunnel was \$292

per cubic foot. The cost of an indoor air bacteria facility is \$104 per square foot and \$5.20 per cubic foot.

Two general conclusions may be drawn from this information. One is that for a facility employing the three variables found in plant growth rooms (irradiation, temperature and relative humidity control), unit capital costs depend on size of facility. They differ in this respect from the construction costs of residential and commercial buildings, where unit costs primarily reflect differences in quality rather than size. The most expensive plant growth room on a square footage basis was one of the cheapest in total cost (\$10,000) but it was also the smallest (15.1 ft.²). The cheapest in area and cubage costs was also the largest in size and the most expensive in total construction cost.

The other general conclusion is that with the wide spread in capital cost of controlled environment facilities in relation to size, and the number of variables and their ranges and precision of control, there is little point in further refining or augmenting the construction cost data collected until the interests of the Sanitary Engineering Center have been spelled out in a post-survey study. The potential cost range is from \$3 thousand to \$6 million, based on survey information. When more specific information is available and requirements can be spelled out even in a general way, the commercially produced pre-fabricated facilities with four of the five cited variables may provide one basis of information on approximate cost. (The excluded variable in these multi-variable package facilities is wind plus the uncited water-wave controlled variable.)

Air Humidity and Temperature Control

In view of the different types of air-conditioning systems encountered, a brief exposition on the methods and principles involved may be helpful. The discussion is mainly concerned with relative humidity control; however, air-temperature change by heating and cooling and relative humidity control are interrelated processes.

Moisture may be removed from air either by cooling it to and below the dewpoint, which varies with specific humidity, or by use of a chemical

absorbent. If an absorbent is used it is regenerated by heat. The principal methods of humidity control are: (1) evaporative process, (2) refrigeration, (3) liquid chemical absorption, and (4) solid chemical absorption. The first three processes are capable of operating over a wide range of air volume; the fourth is restricted to relatively low air and moisture volumes.

All of these methods were in use at the facilities surveyed. With all of them the main design problem was dehumidification rather than humidification capability, since air can readily be humidified by simple devices such as water sprays and steam jets.

The cheapest and simplest method of cooling air is by direct evaporative cooling, using water at a "normal" temperature as the evaporative coolant. Basically, this method humidifies the air it cools. However, it is capable of dehumidifying air to a limited extent under selective conditions and when the air is reheated. Such a condition might be obtained where unconditioned air with a dewpoint of 60°F is cooled to dewpoint temperature to remove moisture and then reheated to 70°F. Evaporative cooling (and heating in cold weather by hot water spray or steam), is carried on at some plant growth room facilities (such as the Climatron at the Missouri Botanical Garden), where only a limited range and precision of temperature and humidity control are desired.

The second method (refrigeration) cools and dehumidifies air well beyond the limits of normal evaporative cooling. Unconditioned air can be cooled to a lower temperature and hence to a lower dewpoint level to remove more moisture. Reheating commonly is required to restore the air to the proper temperature for room conditioning and to lower the relative humidity to some level below 100%. This involves appreciable energy expenditures -- first to cool the air below its desired room-entering temperature and then to reheat it. Dehumidification by conventional refrigeration has distinct temperature-humidity range capability limits.

The third method (liquid chemical absorbents) is inherently humidity conditioning; either after-cooling in hot weather or after-heating in cold weather can be incorporated into the design to

provide complete air-conditioning. Advantages of this method are savings in energy operating costs and in installed horsepower, greater range of dehumidification and high air-volume capabilities. According to one manufacturer offering equipment using lithium chloride, dehumidification to a dewpoint of -90°F and removal of over 97% of air-borne bacteria and molds can be attained by all units. This equipment (Surface Combustion Company's "Kathabar") is offered in a range of 1100 to 15,000 cfm/unit. As with refrigeration, however, air-volume capacity can be expanded indefinitely by use of multiple units. One cited installation has a capacity of 200,000 cfm.

The saving in energy consumption and installed horsepower achieved by a chemical absorbent as compared with dehumidification by refrigeration is due to the fact that it is unnecessary to chill the air to a temperature below its delivered temperature in order to dehumidify it or to reheat the air to the desired temperature level. To illustrate, the manufacturer cited a condition where dehumidification was needed with essentially no change in temperature. The conditions were: 200,000 cfm of entering air at 120 grains of water (72.5°F dewpoint) and 100°F, with exiting air at 63°F and 44 grains (45°F dewpoint). In this case, dehumidification by refrigeration would require 2000 HP vs. 63 HP for the lithium chloride system.

The main disadvantage of this method is the capital cost of equipment. Depending on the particular design conditions of air volume, entering and exiting air temperatures, and relative humidity, this might or might not exceed savings in the cost of alternative dehumidification equipment (refrigeration or a solid chemical absorption system). Where temperature control is of primary interest, and where the relative humidity condition obtained by temperature control per se is acceptable, there would be no justification for special dehumidification equipment.

Where a facility capable of operating over a wide relative humidity range is desired, another indicated advantage of chemical absorbents for dehumidification is that energy consumption is directly proportional to the load placed on the equipment at any time. This is because energy is required mainly as heat for absorbent

regeneration. This is not so with refrigeration equipment which uses energy mainly as power to operate compressors although it can be approached by use of multiple units in large installations.

No technical data have been acquired on solid chemical absorbents (such as silica gel), although equipment of this type was encountered in the survey. Such equipment is understood to be much more limited in air-volume capacity than are the liquid chemical absorption systems. This method is used at the Tempe-Phoenix facility, however, where the ambient air is relatively dry. Its indicated role, accordingly, is in smaller installations or possibly as a supplement to a liquid system to meet extreme requirements of a sub-facility within a larger facility.

Precision of Control

By precision of control is meant both ability to reach pre-determined temperature and relative humidity settings in a controlled environment facility and ability to maintain these settings within a given tolerance range. Precision of temperature and relative humidity control may be classified as follows: (a) Range of control, (b) mechanical control equipment and instrumentation, and (c) air flow rates and air turbulence.

Range of control has important bearing not only on construction and operating costs but also on precision of control and type of mechanical control equipment. In the section on Principal Considerations brief mention was made of the physics of humidity control relative to temperature. As pointed out, the ability of equipment to dehumidify air is directly related to specific humidity as expressed in air-conditioning in terms of grains of water vapor/lb. of dry air.

As an extreme example, at 10% relative humidity air at 95°F contains about 26 grains of water vapor; at 30°F it contains about 2 grains. While further reduction in relative humidity at the lower temperature figure is perfectly possible with some equipment, cost, design and operating problems result which are not present for an equivalent reduction at the higher temperature figure. The questions posed in planning

a facility are: What range is needed? If the range is extreme, must precision of control be uniform over the entire range? And how often will the extreme ranges be used? While these questions apply more to relative humidity control than to temperature control, in principle they are applicable to both.

It is apparent that the design of temperature and relative humidity control should be integrated for both the mechanical control equipment and for the space to be served. While the control equipment should be more precise in tolerance than the design conditions for the space to be served, there is little point in providing mechanical control equipment with a 1% operating tolerance to serve space where the operating tolerance will be, say, 10 to 20%. Where a high precision of control (or a high rate of heat exchange) is demanded in the served space, however, another design and cost problem is introduced. In addition to precision of control in the serving equipment, uniformity of temperature and relative humidity gradients in a served space are achieved by two measures. One is to obtain near-uniformity of air flow in all served space where precision of control is needed; the other is to increase the air-change rate.

The first factor (near-uniformity) requires decision as to the critical space zone in the served space. Is it the entire volume of the space, including that adjacent to lamp banks (where artificial irradiation is employed)? Or is it in a more limited zone such as at plant bench level in a plant growth room? Also, is flow uniformity compatible with expected space occupancy?

The effect of design sensitivity of control on air change rate in the served space is illustrated by the range of air change rates encountered in this survey for non-wind tunnel facilities. This range was from 4 air changes a minute at the Purdue University climate room to 1 change in 6 minutes at the A.R.S. facility at Tempe-Phoenix. (Also, a controllable range of from 2 changes a minute to 1 change in 25 minutes in the CDC-Atlanta air-bacteria facility where a wide range of different air movement rates will be needed for experimental studies).

Aside from the obvious influence which air movement rate exercises on the air volume to be conditioned and hence on the cost, sensitivity and selection of air-conditioning equipment, high air movement rates can be incompatible with other design objectives. The cited A.R.S. facility provides one example. In the early planning stage, very precise temperature and humidity control was considered essential. A very low air velocity in the plant growth rooms was considered equally essential. Advice from A.R.S., Beltsville, was that a temperature gradient of 5.4°F (and a correspondingly higher relative humidity gradient) was commonly experienced in successfully functioning plant growth rooms. Precise temperature and humidity control in the rooms would require air velocities objectionably high for plant transepiration studies. The standards for temperature and humidity control were accordingly lowered to levels compatible with air velocity limitations.

Water-Holding Models

In view of the near certainty that research at the Sanitary Engineering Center would utilize water-holding models if a controlled environment facility were provided, special effort was made to obtain information on the location of indoor facilities in which water was a main environmental medium. Of interest was not the hydraulic testing laboratory, but rather a facility in which aquatic plants (especially algae) are grown, or in which surface evaporation rates might be studied under simulated natural conditions rather than more limited experimental conditions.

Sources of information were the Bureau of Reclamation, Corps of Engineers, Hydrologic Services Division of the Weather Bureau, plant scientists wherever encountered, the National Science Foundation and various literature references. Very little useful information on the location of existing facilities was obtained. It appears that most such are outdoor facilities and hence limited to actual natural local conditions rather than simulated nationwide conditions.

It is well known that algae are raised indoors in flasks and test tubes exposed either to solar irradiation or to a single vertical fluorescent lamp paralleling the growth medium container.

The A.R.S. Soil and Water Conservation Branch has a Plant, Soil and Nutrition Laboratory at Ithaca, New York, which specializes in studies using the unicellular green alga *Chlorella* as a test organism. According to Thompson⁽³²⁾, *Chlorella* has been grown indoors by "shaking or bubbling air at 21°C. It has been grown both in darkness and in light with CO₂ or sugar as a carbon source. All light has been supplied with fluorescent bulbs so this alga apparently does not require red light for normal growth as do the higher plants."

Reisner and Thompson⁽³¹⁾ describe a "large scale" unit consisting of a battery of 5 vertical culture tubes, each 2 ft. long and 2 mm. I.D. The irradiation was provided by a battery of 4 horizontal fluorescent lamps in a vertical tier, of such wattage and at such distance (9 inches away), as to provide "about 400 ft.-c."

Carnegie Institution Publication 600 (20) describes many algal growth chambers of the glass flask and test tube type; nearly all of the algae growth pools described, however, are natural daylight type, either outdoors or in the greenhouse.

An artificially irradiated algae "pond" 1 cubic meter in volume was described in an account of a proposed pilot type pond in Israel. It was stated that such a pond should be at least 1 m. deep -- to utilize high-intensity light more efficiently by lighting in depth, and to have a large ratio of volume to surface area in order to decrease infrared heating effects. Both solar and artificial irradiation were discussed. It was proposed to provide indoor irradiation with a bank of 23 40-w. fluorescent lamps per square meter. The distance between the lamps and the water surface, and their value were not given.

Van Der Veen⁽³³⁾ briefly discusses aquarium lighting. Interest is centered on home type aquaria for plants larger than algae. Very little detail is given, but it is stated that either tungsten or fluorescent lamps may be used and that for tungsten lamps about 2 watts per day per square meter are required.

In spite of this paucity of information on indoor artificially irradiated ponds of a "model" type, certain hypotheses can be developed with respect to some requirements of the Sanitary Engineering Center facility:

1. Rather high-intensity artificial irradiation is indicated in spite of the low irradiation requirements of the index alga Chlorella (about 400 ft.-c.). Interest in such a model probably would not be to grow algae per se, but to simulate the biochemical and physical conditions in a pond in nature. This requires that there be sufficient light intensity to penetrate the water to an adequate depth.

2. Fluorescent lamps probably would be preferable since a level of up to 7000 ft.-c. can be obtained, they would tend to avoid overheating the water, and they are more efficient and less costly to cool.

3. There may be need for a broad light spectrum, except for those wave bands in which almost immediate conversion into heat takes place within the absorption spectrum of water, as all principal marine and fresh water algal groups may be of interest to the Sanitary Engineering Center.

Of the seven major divisions of algae, the species of only two divisions are all grass green in color⁽²⁰⁾. In two of the remaining five divisions, other photosensitive pigments are predominant over chlorophyll. In the remaining three divisions other pigments are important and in the two grass green divisions other pigments are present. Accommodation of the total spectrum of obligate and facultative phototrophic algae may require consideration of light quality values beyond those in the zones of maximum photosynthetic activity, and this need may not be gauged solely by the requirements of Chlorella. It is considered likely, however, that these needs would not extend beyond the supplementation of fluorescent lamps with filament lamps as is the practice in terrestrial plant growth rooms.

Further study would be necessary for detailed consideration of the controlled environment requirements of models of oxidation ponds, water supply reservoirs, and other impoundments. Brief mention can be made here of winds and waves, since these are pertinent to fitting together the various combinations of variables cited for a controlled environment facility. Three

assumptions are made at this stage. First, mechanical methods of creating water waves in a model would be far more suitable and dependable than an attempt to create wave action by surface air velocity. Second, the remaining need for wind would be to provide a slow rate of air movement at the air-water interface to meet heat and gas exchange needs, plus possibly ripple movement which might not be readily achievable by mechanical means. Whether a higher air velocity would be required for ripple action than for air change is a moot point in determining the feasibility of combining different variables in a single controlled environment chamber. A low air movement rate is within the capability of conventional air-conditioning. A substantially higher rate could be incompatible with air processing for temperature and relative humidity control.

Third, a wave-maker could be shorter in channel length at the Sanitary Engineering Center than at the two facilities described in the Appendix.

Combinations Of Variables In A Single Facility

The term "facility" as used here could mean a structure in which all of the variables are applied interdependently in the same space or else a complex of differing substructures. A facility in which a model could be subjected to all of the cited natural forces under simulated "natural" conditions is one providing controlled interdependency and interaction of all variables. This was found to some extent in the facilities visited.

In the present survey, three-and-a-half variables were commonly encountered in the same facility, if a value of one-half is given to controlled air movement (an element of air-conditioning) as partial credit toward the "wind" variable. The full value variables, simulated solar irradiation, temperature, and relative humidity control were commonly encountered together and obviously feasible in a single facility.

At least three commercial companies are producing a controlled environment facility including another variable, simulated altitude. Many such units have been built and are in use. Thus it may be assumed feasible to combine

four-and-a-half variables into a single facility within prescribed limits and for certain uses.

There is no reason why some type of equipment to make waves could not be incorporated in a hydraulic facility, giving five-and-a-half variables. The remaining half variable (wind as distinguished from air movement) is theoretically possible in a combined facility, but perhaps not practical from the standpoints of cost and necessity.

Accordingly, there are two principal areas of uncertainty with respect to the feasibility of a combined facility. These are singled out to distinguish them from the very large number of minor areas of uncertainty pertaining to need for combining, range, precision, etc.

The first problem relates to the need for incorporating wind (up to 20 mph) in combination with all other variables. Incompatibility is involved with temperature and humidity control by conventional air-conditioning processes. Increased facility size would be necessary. There might be uncertain effects on a small model. Partial substitution by water wave-making equipment is possible.

The second principal area of uncertainty is the potential incompatibility of simulated altitude control with over-all facility shape, area and cubage requirements, as well as with other variables. Simulated altitude control alone can be economically provided by units conforming to rather limited dimensions. For example, a prefabricated structural shell 9 ft. wide, 7 ft. high and 14 ft. long costing \$12,000 can withstand an "altitude" of 50,000 ft. Complete with mechanical equipment for conventional air-conditioning, a similar chamber for the same altitude requirements is priced at \$29,468.

Applied to a facility designed to include the other needs of the Sanitary Engineering Center, however, the potential cost of providing simulated altitude throughout the facility could become very high even though the altitude requirement of 50,000 ft. were cut back greatly. Expense would be for mechanical evacuating equipment, for added structural strength, and for pressure sealing.

As an index of structural strength requirement, dead loads on a hemispheric shell facility 50 ft. in diameter are given below for 5000 and 10,000 ft. of simulated altitude. The value of 10,000 ft. has been selected because it is probably the highest the Sanitary Engineering Center would want for model studies under non-space conditions; 5000 ft. is perhaps the lowest compromise level.

With the hemispherical surface area of 3930 ft.², the dead load conditions due to vacuum would be as follows:

	5000 ft.	10,000 ft.
Unit load, psi	2.3	4.6
Unit load, psft	330	660
Total load, tons	650	1300

The dead loads for the larger Climatron at St. Louis would be 7.8 times as great or 5050 and 10,100 tons respectively. In the event a Government-surplus shell suitable for other controlled environment needs were to be utilized, however, the cost problem might be solved but could be replaced by problems of adaptation to other variables.

The alternative to an all-in-one facility would be to follow the subchamber principle. This was commonly encountered in the survey although not in an arrangement as indicated for the Sanitary Engineering Center.

From the standpoint of incompatibility and construction cost, the first two variables to be separated from the others would be wind and simulated altitude. While the water wave-making variable probably could be incorporated in a facility containing the remaining variables, it is likely that waves and wind should go together as in the Gainesville, Florida, wave-wind facility. On this basis, a facility might consist of:

- a. A main facility with temperature, relative humidity, artificial irradiation and moderate air movement as variables.
- b. A subfacility with water waves and wind as variables.
- c. A subfacility with simulated altitude as the basic variable. This might function alone or in combination with any or all of the variables in Item a.

Whether any or all of these facilities would fit the needs of the Center lies within the scope of another study.

Joint Development And Use Of A Controlled Environment Facility

Use of an existing facility might be contracted for testing under extreme range conditions or a special variable seldom used. For example, the Purdue University facility has a low temperature capability of -30°F in common with some other variables. If a minimum sustained temperature of 20°F (sufficient for ice cover in a hydraulic model), were needed 99% of the time and a lower temperature only 1% of the time, it might be logical to design a new facility for 20°F and rely on Purdue for the lower temperature work. This would not only save construction cost but reduce operating cost and complexity.

At the Sanitary Engineering Center, a likely objective might be to simulate the more commonly occurring natural conditions in the U.S. climate, rather than bizarre conditions. In

planning a facility, there may be a tendency of the investigators first "to ask for the moon" in terms of range and precision. With progress in design, impractical or incompatible objectives, or non-essential capabilities are, hopefully, eliminated. The hallmark of the experienced operator in the controlled environment field, or the experienced engineering designer, is the degree to which the design and functioning of the facility and its equipment are simplified and yet achieve the intended purpose.

The second possibility for a joint facility is its development and use by more than one element of the Sanitary Engineering Center such as by Water and Air Pollution Control research units.

A rational approach in planning would seem to be:

- a. Provision of separate facilities to satisfy the routine needs of each element;
- b. joint use of rarely needed facilities; and
- c. common central mechanical equipment, mechanical operating staff, repair facilities, and instrumentation specialists.

CONCLUSIONS AND RECOMMENDATIONS

General Conclusions

The controlled environment facilities covered by this survey and report comprise only a few of those believed to exist. Field travel information indicates that the use of at least some types (outer space and plant growth room facilities) is rapidly growing. One index of the prevalence of these facilities is that there are at least five manufacturers of such facilities. In a sampling of ten United States universities by persons interested in only one specialized area (bioclimatology), controlled facilities were located at every school.

From the prevalence and diversity of controlled environment facilities and their continuing use and increased numbers, it can only be concluded that they are feasible and useful for a wide range of investigations. Accordingly the issue posed in a contemplated facility is how ambitious planning should be with respect to type of use, range of controls, degree of sophistication, etc.

A controlled environment facility obviously should be viewed as a tool to be used in company with other facilities, methods, and procedures. A facility designed to simulate more or less a combination of natural conditions cannot supplant laboratories where rigid standardization under selected artificial conditions is desired to explore fundamental laws or apply them under repeatable conditions and results. In contrast, a facility intended to simulate natural conditions may appropriately reflect the inconstancy of natural biologic and climatologic conditions -- the fact that they are always in a state of change.

Experience with plant growth rooms indicates that natural conditions need to be simulated not with the highest possible degree of precision but only approximately in a controlled environment facility dealing with outdoor biological processes. Any organism with the capacity to flourish under ambient conditions has within it a tolerance to change. The degree of tolerance varies with species, and there is an optimum range for each.

A controlled environment facility should be as simple as possible consistent with intended purpose.

A facility should be designed with flexibility for adaptation of space, changes in use, and modification of control.

The planning and design of a successful permanent facility is apt to be a rather prolonged operation, requiring the attention of specialists. Government agencies bound by inappropriate regulations may face a considerable disadvantage in this respect, although private agencies have not been universally successful in avoiding difficulties either. In the development of existing or future controlled environment facilities, the full use of design engineers specializing in this field will be essential to success.

Recommendations

Since controlled environment facilities have been found feasible, the logical recommendation is that this survey be followed by a study of Sanitary Engineering Center needs for such a facility for research. The advantages of various alternative proposals to fit these needs should be investigated.

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The literature review comprised an important part of this survey, including manufacturers' catalogs, reprints of technical articles, reports, books, and serials.

These sources were consulted for technical information on manufactured products in the controlled environment field, the location of controlled environment facilities, their characteristics, and on technical and scientific data to provide perspective for a more adequate understanding and evaluation of the facilities visited and the basic processes involved. Information

abstracted has been used extensively in preparing this report.

The references have been categorized into sections on Climatology, Meteorology and Physics, and Plants and Radiant Energy. Included also are reviews of several books that were found to be of special interest. Library facilities included the Public Library and the Emory University Library in Atlanta, Georgia; the U.S. Dept. of Agriculture Library in Washington, D. C.; the Missouri Botanical Garden Library at St. Louis, Missouri; and the Public Library of Dallas, Texas.

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Book Reviews

CONTROL OF THE PLANT ENVIRONMENT, Hudson, J. P. (26): The proceedings of a symposium held in 1957 at the University of Nottingham, the book consists of 22 chapters, grouped into four main parts which deal with the effects of the environment on plants, control of environmental factors for plant experimental work, installations for the control of plant environments, and demonstrations. The book discusses only terrestrial plants and is concerned with the development and use of controlled environment facilities either to reduce variability in plant experimental studies and thus encourage replication of results, or to grow experimental plants out-of-season or in a foreign climate. Mention is made of knowledge of some 70 controlled environment installations for plant growth studies and of "upward of a hundred papers on the development of controlled environments in possession of the author in a mimeographed bibliography available on request."

The factors considered are mainly irradiation for plant photobiologic and thermal requirements, temperature, relative humidity, and air movement as an element of air condition. g. There is a short description of plant wind tunnels that were designed to measure rates of water loss in plant-soil systems under constant temperature and relative humidity conditions.

No information is given on construction or operating costs for the controlled environment facilities described.

PHOTOSYNTHESIS AND RELATED PROCESSES, Rabinowitch, E. I. (30): This is a basic reference in three volumes on spectral light quality and algae development. Volume I deals with the chemistry of photosynthesis, Volume II with spectroscopy and fluorescence, and the third volume with kinetics. Information in Volume I indicates that the relationship between algae and the spectral quality and energy aspects of solar irradiation are not such as to warrant separating algae from terrestrial plants. Rather, many statements are made about plant life in general which are based on algae studies.

LIGHT AND PLANT GROWTH, Van Der Veen, R. and Meijer, G. (33): An excellent book on the relationships between irradiation and plant growth. In addition to dealing with the physics and plant biology of irradiation over the solar spectrum range, a small growth chamber at the Eindhoven, Holland, plant laboratories of the Philips Lamp Company is briefly described. The room is about the same size as the one at Emory University and is used to study the effect of various light colors on plant growth.

EXPERIMENTAL CONTROL OF PLANT GROWTH, Went, F. W. (35): The author is concerned basically with the results of studies with a phytotron at the California Institute of Technology in the Los Angeles area. Completed in 1949, the operating period covered seven years. The Phytotron has a total of 54 controlled environment plant growth rooms and compartments in which terrestrial plants are held for sustained periods or, more commonly, moved frequently. The environmental condition in each space is held constant and is continuous in operation; the plants are moved on wheeled carts to another space whenever a change in conditions is desired. The controlled environment factors are irradiation for plant photobiological and thermal requirements, temperature, and relative humidity; there is an artificially illuminated rain-room and also dark rooms. The plant space includes air-conditioned greenhouses, growth rooms and growth compartments.

The book is divided into three main parts: Construction and operation of the laboratory, climatic response of individual plants, and general discussion (which deals mainly with an analysis of biologic variability in plants). Both practical and theoretical information is furnished, including layout drawings and a breakdown of construction costs. The Phytotron, with an area of 15,000 ft.² cost \$417,000, including office, ancillary and utility space. Operating cost, including salaries of operating personnel and repairs, was \$60,000 per annum.

Special features of the Phytotron are the use of activated carbon to filter the outside air supply for control of Los Angeles smog; decontamination procedures to prevent admission of insects and infectious microorganisms in the air supply, seeds, soil media and personnel; and a traffic control and room use schedule.

This book will be of much value to those concerned with the planning, development and operation of controlled environment facilities for plant growth purposes. It has a bibliography of 181 references.

APPENDIX

Notes On Facilities Visited

Facility: Climatron at Missouri Botanical Garden.
Location: 2315 Tower Grove Ave., St. Louis 10, Mo.
Contact: Dr. Frits W. Went, Director
Age of Facility: Structure and Equipment - about 1 year;
instrumentation - not yet installed.

GENERAL DESCRIPTION OF FACILITY

The Climatron is a Plexiglas hemisphere for growing tropical vegetation. It is a vital element in a plan of redevelopment and expansion of the century-old Missouri Botanical Garden and is the first step in this plan.

Other elements of the plan involve the rehabilitation and construction of plant research laboratories and administrative facilities, aided by facilities development support from the National Science Foundation and the National Institutes of Health. The primary purpose of the Climatron is public education and recreation, with some ancillary value as a research facility in tropical plant development. It is also expected to play an important indirect role in botanical research; anticipated revenue from visitors will help to support general grounds upkeep, thus freeing endowment income for research.

The present director, Dr. F. W. Went, a widely recognized leader in botanical research, developed a Phytotron facility while at the California Institute of Technology, and has now developed the Climatron in his present capacity.

The Climatron structure is a Fuller geodesic dome, with Plexiglas panels supported by an aluminum alloy structural tubing framework. It is 175 ft. in diameter, has an approximate volume of 10^6 ft.³ and has the general shape of a hemisphere. The interior ground space is occupied by a 2-level tropical garden. The lower level, a

sunken garden, occupies about one-third of the area of the enclosure and the upper level, which is about 12 ft. higher and at ground level, occupies the remainder.

Mechanical equipment is housed under the upper level, with access from the sunken garden.

The entire garden area is in a single enclosure; there are no partitions. In spite of this, four principal climate zones are obtainable within a tropical climate range in the enclosure, mainly by the ingenious management of air movement.

DETAILED DESCRIPTION OF FACILITY

Construction Cost. Rounded construction costs are itemized below:

<u>Item</u>	<u>Cost</u>
Concrete Base	\$ 60,000.
Plexiglas	130,000.
Aluminum Framework & Foundation	260,000.
Subtotal - Structure	\$ 450,000.
Air Conditioning	150,000.
Planting, Landscaping, Design, Utilities Services, Plumbing & General Overhead	100,000.
Total	\$ 700,000.

Based on a circle 175 ft. in diameter, this represents a unit cost of \$34. per square foot. Volumewise, the unit cost is \$0.70 per cubic foot.

Operating Costs. Due to the brief operating experience, little data is available on operating costs, especially repair, replacement and maintenance costs. No information was obtainable on operating labor costs.

In spite of the much larger cubage of the Climatron than the non-tropical greenhouses it replaced, it is stated that the heat load is about the same in spite of the fact that the greenhouses were kept at a much lower temperature. This is attributed to air leakage from the old structure.

Although high-intensity lighting is not employed, the power load of the light installation is substantial (130 KW), due to large size of facility. However, it is reported to operate only about 12 hrs./week in the winter and presumably is not needed for plant photochemical processes in other seasons.

The exhaust fans (20 HP total capacity), are practically never in operation in the winter, presumably because of lack of excess solar heat irradiation in the Climatron. In the winter a 15 HP circulating fan and a few pumps totalling 2 HP are in operation.

If this 17 HP of motor equipment were to be operated continuously in the winter, the energy cost for lights and motor power is approximated below, based on the General Service Rate Schedule of the Savannah Electric and Power Co., after excluding the high unit rates of the first 2500 KW hrs. of demand (since the Climatron is part of a larger Botanical Garden complex).

	<u>Per Month</u>
Motor Load $17 \times 0.745 \times 720$	9140 KW hrs.
Lighting Load 130×12	1560 KW hrs.
Total	10,700 KW hrs.
(Installed KW - 143)	
1st 2500 KW hrs. @ 1.9¢	47.50
Next 8200 KW hrs. @ 1.6¢	131.20
Long Hours Use Charge - None	
Demand Charge - None	
Total	\$ 178.70

The 17 HP of motors probably does not operate continuously. At 50% operating time, total energy consumption would be 6130 KW hrs. and the electric bill would be \$105.58. These energy charges should be appraised in relation to the square footage and cubage of the facility.

Operating Ranges. A temperature differential of about 10° F and of about 30% in relative humidity (both at plant levels), are considered obtainable within the enclosure. The precise values of these gradients and the sensitivity of control cannot be stated until instrumentation has been installed. Extended delay has been experienced in delivery of the instrumentation by the manufacturer.

The design daytime temperature values in the enclosure are from 80° to 90° F in summer and from 70° to 80° F in winter. The design nighttime values are from 60° to 70° F. These ranges reflect the temperature gradient in different parts of the garden.

Air Supply. For the purpose of describing the air supply system, the low-level garden might be visualized as occupying Quadrants 1 and 2 and the high-level garden as occupying Quadrants 3 and 4, although the chord separating the two pairs of Quadrants does not pass through the center of the circle since the low-level garden is smaller in area than the high-level garden.

There are two separate air-conditioning systems which can work either independently or together. It is this feature together with the spacing of the inlets and outlets of the two systems, and the two different floor levels, which permits four different climatic zones to be maintained at ground levels in a single enclosure.

System 1 has ambient air inlets and exhausts. Air entrance is through a battery of large louvered panels set in the peripheral wall of Quadrants 1 and 2. They extend in height from the floor level of the sunken garden to the floor level of the upper level garden. Immediately after passing through the louvers into the main enclosure, the entering air can be conditioned by a water spray system mounted in the wall for humidification, heating and cooling.

When operated as an independent system, this air is rejected to the atmosphere through a battery of 20 slow speed, large diameter noiseless-type exhaust fans located near ground level in the peripheral wall of upper-level Quadrants 3 and 4.

System 2 is a recirculating air-conditioning system with conditioned air from a tunnel admitted through louvered wall panels in Quadrants 1 and 4 and exhausted through louvered panels in Quadrants 2 and 3, following which it can be adjusted for temperature and humidity before being recirculated. There is also a small intake damper in this system for admission of outside air into the air-conditioning system.

Irradiation. The Climatron depends primarily on solar irradiation through the Plexiglas dome for plant photosynthesis. However, it is equipped with floodlights for night display purposes and these also can provide low level supplementary lighting on short or cloudy days.

Mechanical Equipment. The limited design temperature and relative humidity ranges help to simplify the air-conditioning system and reduce unit capacities and costs. The \$150,000 investment in the air-conditioning plant for example, represents a unit cost of only 15¢ per cubic foot equivalent to \$1.50 per square foot for a room with a 10 ft. ceiling. These cost figures include humidity control as well as temperature control and cooling and air change rate capacities needed to overcome the effects of high solar irradiation values during sunny summer days.

There are no compressors in the mechanical room, only evaporative cooling being employed. Heating is by conventional air-conditioning equipment. Humidification of recycled air is achieved by atomizer type spray nozzles which also provide evaporative cooling. There is no dehumidifying equipment because the lowest desired relative humidity (60%), can be achieved by air temperature adjustment. A hot or cold water spray for temperature and humidity adjustment can be applied to the ambient air admitted directly into the hemisphere.

GENERAL DISCUSSION

Spectral Light Quality. In a general discussion of spectral light quality and plant processes with Dr. Went, he stated that the rounded-off values of light wave bands utilized by plants in photosynthesis were from 4,000 to 5,000 and again from 6,000 to 7,000 Angstrom units. The 5,000 to 6,000 wave band range represents a green color range verging into yellow which is not utilized to any extent and high light intensities in this band are even inhibiting.

In the shorter wave lengths, the lowest wave length reaching the ground surface in significant amount is 3100° A, but in terms of effective influence from an energy standpoint the lowest value is around 3600° A. Ordinary window glass and Plexiglas are efficient filters of radiation in the 3100 to 3600° A range.

The term "near red" as used in plant research is visible red light, while the term "far red" is infra-red light between 7,000 and 8,000° A.

Ultra-violet irradiation in the 2,600 to 2,800° A range is most destructive to plant tissue. However, the amount reaching the ground surface even at high elevations is insufficient to damage plant tissue.

About half of the total energy in the solar spectrum reaching the ground surface is in the visible light range. A typical greenhouse glass roof removes about 40% of the solar irradiation at the earth's surface, practically all of the remaining 60% is absorbed by the plant and soil surface rather than in passage through the air within the greenhouse.

In addition to the known effects of spectral light quality (i.e. different wave lengths), and of photoperiodism on plant growth, Dr. Went stressed the importance of length of time of irradiation within the diurnal cycle. He cited as one example that many plants could not stand continuous light and also mentioned that light and temperature could be substituted for each other in some plant response studies.

Facility: Technical Development Laboratories, Communicable Disease Center, U. S. Public Health Service,
Location: Oatland Island, about 10 miles from Savannah central business district. (Box 769, Savannah, Ga.)
Dates Visited: November 25, 1960, December 7, 1960 and February 7, 1961.
Contacts: Mr. L. B. Hall, Chief; Mr. Peter Skaliy, Bacteriologist; and Mr. Kenneth Goddard, Air-Conditioning Engineer, all of the Bio-Physics Section.

GENERAL DESCRIPTION OF FACILITIES

The original purpose for visiting the Oatland Island Station was to obtain detailed information on an 8 ft. cubical controlled humidity chamber (first built about 1955) for calibrating and testing different types of bacteria-in-air samples. It was found later, however, that more recent facilities were of greater interest.

Recent facilities developments are a new controlled environment facility being constructed at Oatland Island and a larger one being planned at CDC Headquarters in Atlanta, Ga. Both have the same objective, namely the study of bacterial movement, removal and survival in the air of interior spaces under conditions which either simulate those in such places as hospital rooms, including surgeries, or under highly standardized conditions for more basic studies.

The controlled variables are temperature, relative humidity and air movement within the parameters of an air-conditioning system. Because of the nature of the studies, all three facilities are characterized in design by the objective of obtaining a very high order of sensitivity and precision of control of the three variables, at least in terms of influent air characteristics.

In this respect the CDC and the Purdue University facilities are somewhat comparable in that the air-conditioning and sensing equipment are sophisticated. They are in contrast to most of the plant growth rooms visited where interest is mainly centered on artificial irradiation and relative humidity is considered mainly captive to the air temperature changes which take place both in nature and in the growth room.

DETAILED CHARACTERISTICS OF FACILITIES

Scattered information was obtained from Messrs. Hall and Skaliy, with most of the detail dealing with the mechanical equipment and its control being obtained from Mr. Goddard. Attention was directed to the two new facilities. Since more data was available on the larger facility designed for use at the CDC Atlanta facility, discussions were mainly on that design.

In earlier conversations with Messrs. Hall and Skaliy, however, emphasis was placed by both on the need for sensitivity of relative humidity control in the CDC facilities. This involves both sensitive humidification-dehumidification equipment and sensitive sensing devices. The main mechanical equipment problem according to Hall is expected to be met by the use of lithium chloride dehumidification equipment and the sensing problem according to Skaliy is being met by devices made by the ElectroMatic Products Co., 2233 Knox Ave., Chicago 39, Ill.

Design of the CDC-Atlanta facility's air-conditioning system was being carried on by Mr. Goddard, who was also supervising the construction work under way at Oatland Island by force account.

The CDC-Atlanta facility is a 40 ft. by 60 ft. penthouse, with a 20 ft. ceiling height. Within this overall space there will be two main test chambers occupying about 50% of the total space. The remaining space will be used for a workshop, mechanical equipment and controls, walkways, air locks and dressing rooms around the two separated chambers. The total area is 2400 ft.² and the total volume is 48,000 ft.³

One of the chambers is called a mock-up and controlled atmosphere chamber, the other is a

three compartment chamber with a cloud sub-chamber, a personal hygiene subchamber and a control subchamber between them.

The general purpose of the mock-up and controlled atmosphere chamber is to permit placing equipment and personnel in it to simulate a surgery and other hospital rooms in order to study the behavior of bacteria in air and on surfaces under air movement variables and other introduced factors under known temperature and relative humidity conditions. The general purpose of the personal hygiene subchamber is to study the dissemination of bacteria in air from human subjects. These two facilities will be subject to more or less the same range and control precision with respect to the environmental variables.

The cloud chamber is used to study the movement of bacteria in air under a higher degree of precision of control of the environmental variables, especially air movement characteristics. This includes the objective of obtaining near-laminar air flow conditions at extremely low velocities to measure, among other things, settling rates of air-suspended bacteria. Air inlets and exhausts will both be under positive control.

Space outside the chambers will be air-conditioned by the same central mechanical equipment used for the chambers. Extending from air ducts along one of the long walls of the over-all space are five air-mixing boxes, each of 1500 cfm constant rate capacity for mixing hot and cold air to serve the over-all space and the 3-compartment chamber. Because of special requirements, the controlled atmosphere chamber will be served by two or three of these boxes as may be required.

Summary of Mechanical Features

Relative Humidity Control Equipment. Mr. Goddard advised that excellent control of relative humidity could be obtained with either a properly designed glycol-water system or a lithium chloride system. For CDC purposes, he prefers the glycol system because, unlike the lithium chloride system, it is bactericidal.

The two major manufacturers of the lithium chloride type of equipment with added inhibitors are the Niagara Blower Company which employs lithium chloride (Niagara Hygron), and the Surface Combustion Company's Kathabar. The CDC facilities use Kathabars because they require only a cooling tower for heat rejection while the Niagara equipment also requires a chilled water cooling system.

It was stated that these lithium chloride systems can maintain relative humidity within 1% on a straight line basis over the design range.

Design Ranges. The design relative humidity range is 25% to 95% and the design temperature range is 30° to 100° F.

Air-Mixing Boxes. Use of the air-mixing box principle at points of delivery rather than air-mixing at a single central point for temperature and humidity control is an important element in obtaining accuracy of control and differential control.

The air-mixing boxes in the CDC facility are made by the Connor Engineering Co. of Danbury, Conn. and are reported to cost only one-third as much as comparable competitive equipment. This is due to simpler design. These air-mixing boxes have thermostatically controlled dampers to vary the proportion of hot and cold air for temperature and relative humidity adjustment at a constant mixed air-flow rate.

Air Change Rate. The gross air change rate is based on a total air inflow of 7500 cfm (5 air mixing boxes @ 1500 cfm), into 4800 cubic feet of space. This amounts to 1 gross change each 6.4 min. Air changes in individual test chambers can be set to occur every 2 min.

In this connection, it was mentioned that the British use the term "effective ventilation rate" based on the gross air change rate less a slippage factor which approximates 40% under average conditions.

Breakpoint in Temperature Control Cost. It was stated that it is possible to cool a room to about 40° F with a conventional air-conditioning system. Below that point panels and/or refrigerant pipes are needed in the room or room walls and floor. This materially increases construction cost. The next breakpoint would be at about 0° F where a different refrigerant would be required.

It was also noted that in addition to increased negative heat losses from a controlled environment chamber under low temperature conditions, the unit power requirements for cooling the refrigerants themselves increase with declining temperature. At conventional air-conditioning temperatures the rule is 1 HP per ton of refrigerating capacity, reflecting compressor power requirements. This increases to around 2 HP/ton at 0° F and 4 HP/ton at around -20° F. (Note: 1 ton of refrigerating capacity equals 200 Btu./min.).

Heat Exchanger. Because of the nature of the CDC studies, it is not practical to recirculate the conditioned air. For that reason an uncirculated air-conditioning system is used. By using a heat exchanger for the rejected and fresh air, the power requirement for heating is reduced from about 300 HP to 150 HP. The heat exchanger to be used is made by the Heat Recovery Corp., 669 Mt. Prospect Ave., Newark 4, N. J. It is a revolving disc heat exchanger with woven fiber glass or woven aluminum used in the disc as a heat exchange medium. The position of the disc is normal to the adjoining air ducts for rejected air and fresh air supply. The manufacturer's

catalog claims a heat exchange efficiency of over 80% within recommended design ranges. Fifteen sizes and types are offered at FOB prices ranging from \$2,100. to \$12,700. The three largest standard models cost from \$4,650. to \$8,600, have drive motor horsepower of 3/4 to 2 HP, and can handle 5,000 to 30,000 cfm of air.

CONSTRUCTION COST

The estimated construction cost of the overall CDC-Atlanta facility is about \$250,000 including the structure. The unit costs are \$104. per square foot and \$5.20 per cubic foot.

Facility: Ray W. Herrick Laboratories for Research in Refrigeration and Climate Control. (Also Known as the Purdue Center for Research in Refrigeration and Climate Control).
Location: Purdue University, Lafayette, Indiana.
Contact: W. E. Fontaine, Professor of Mechanical Engineering.
Age of facility: Present building dedicated June 1960.
Date visited: December 13, 1960.

LABORATORY PROGRAM AND OBJECTIVES

This is a non-profit contract laboratory testing facility which has been developed primarily under the aegis of engineering and agricultural experiment stations at Purdue. The broad objectives of the facility are two-fold:

"1. To educate exceptionally gifted students on the graduate level in all aspects of climate control, and to provide a manpower pool of scientifically trained young men who will, by virtue of their education and contacts in the Center, have a real interest in the industry.

"2. To provide a center for the collection, analysis, correlation and dissemination of scientific data on all aspects of climate control and thus serve education, science and technology, industry, and agriculture through greater knowledge in this area."

The Laboratory defines "climate control" as control of air temperature, air composition (including moisture content, impurities and odors), air movement, noise and light. It is concerned not only with basic research into the physical processes and equipment for obtaining this climate control, but also with the effect of climate control on life processes. To accomplish these goals, the Laboratory interdependently works with both engineers and life scientists.

The areas under investigation are:

1. Energy and mass transfer.
2. Sound and vibration control.
3. Thermodynamic properties of refrigerants and liquid absorbents.
4. Air conditioning, heat pump and refrigeration system analysis and control.
5. Thermoelectric cooling and heating.

6. The effects of the climate environment on:
 - a. Nutritional requirements of domestic animals.
 - b. Fertility and prolificacy of animals.
 - c. Efficiency of production of meat, milk and eggs.
 - d. Animal health.
7. Effects of climate on the well-being and performance of man.
8. Processing and preservation of perishable materials.

Stress is placed on the role of the Center as a focal point for applied research of interest to industry. To this end, an industrial advisory committee has been formed and the sponsorship of industry is sought to provide continuing financial assistance.

The Laboratory is under the joint direction of W. E. Fontaine, Professor of Mechanical Engineering, and F. N. Andrews, Head, Dairy Science and Director for Physiological Research. As a result, the present program emphasizes research under both item 6 of the foregoing list and on mechanical engineering research (items 1-5).

Basic research at the Laboratory is carried on as a direct element of the University's research program and also by direct contract with industry and other agencies.

The present research program includes one or more grants from the Research Grants Division of the National Institutes of Health.

GENERAL DESCRIPTION OF FACILITIES

The over-all space of the Herrick Laboratory Building is some 40,000 square feet, divided into 3 wings and representing a construction cost of over \$1 million. The center wing contains office space, hot and cold rooms and a sheet metal shop, with plans under development for sound and noise research facilities.

The west wing, (120 by 60 ft. or 7200 sq. ft.), consists of a large mechanical engineering laboratory for fundamental research in the areas of thermodynamics, fluid mechanics, heat and mass transfer as they affect problems in climate control. Equipment includes temperature measurement and recording instrumentation, flow measuring devices, sound and vibration measuring, analyzing and recording instruments, low vacuum equipment and instrumentation,

psychrometric instruments, pressure indicators, and recorders. The investment in portable instrumentation alone is reported to be \$100,000 and the staff of 3 full-time technologists employed mainly in the west wing facility includes an instrumentation specialist. There is a special instrumentation shop.

Equipment of interest in the mechanical engineering laboratory includes:

1. A vacuum chamber capable of achieving a vacuum of 0.015 microns of mercury or about 5/100,000 of an atmosphere. The outside dimensions of this steel chamber are about 3.5 ft. in diameter and about 6 ft. in height. The vacuum is obtained by a small diffuser pump and a rotary pump in tandem hookup.
2. A small wind tunnel for mass transfer studies.
3. A fluid dynamics wave flow machine consisting of a long horizontal transparent tube about 2 inches in diameter for investigation of laminar, turbulent and annular flows.
4. An altitude chamber about 4 ft. by 4 ft. by 4 ft., capable of a simulated altitude of 90,000 ft. (Cost \$60,000.)
5. Small low temperature cabinets capable of reaching -150° F.

The east wing is of primary interest in this survey and comprises two controlled environment chambers (identical), and a mechanical room. The environmental variables in the two chambers are temperature, relative humidity, and limited artificial lighting and air movement controls. Following is a detailed description of the chambers and some features of the mechanical equipment serving them.

DETAILED DESCRIPTION OF CHAMBERS

Each of the two control chambers in the east wing has a volume of about 3500 sq. ft. and is divided into two rooms separated by a temperature lock. The main room is 18 ft. by 21 ft. in inside dimension and is totally bare of any fixtures protruding from the walls, floor or ceiling. The smaller room which serves both as an entrance to the main room and as a separate test room, is 9 ft. by 13 ft. and is similar in appearance to the main room except for a large capacity platform scale set in the floor. Both rooms are finished in green ceramic tile and have a ceiling height of about 8 ft.

Two rooms in the center wing were visited where applied animal physiology studies (mainly involving poultry), were underway. These two rooms were kept at two different constant temperature levels simulating ambient conditions in order to measure differences in weight gain by the poultry. Artificial lighting simulating more or less normal poultry room lighting was provided. The rate of air change was adjusted to the extent needed to determine odor control requirements in a poultry room.

Construction Cost. The approximate construction cost of the two east wing chambers and their mechanical room was \$600,000, as detailed below:

Mechanical equipment -- capital cost	\$150,000
Mechanical installation cost - equipment, ducts, plumbing etc.	320,000
Subtotal -- all mechanical costs	470,000
Control panel and controls	35,000
Structure, including chambers (rounded value)	100,000
Total	\$605,000
Total Cost/cu. ft. of chamber (7,000 ft ³)	\$86.40
Total Cost/sq. ft. of chamber (990 ft ²)	\$611.00

Operating Costs. The controlled environment phase of the over-all facility requires one full-time mechanical maintenance man. His salary is not known but an approximation might be \$5000 to \$6000 p.a.

The total connected energy load of the east wing chambers is about 300 KW, including about 225 KW of compressor motors.

The facility is too new for experience to have been acquired on energy costs. In a facility having as great a range of temperature control as this one (-30° to 130° F.) such costs are very difficult to predict since they depend so much on the requirements and duration of the particular experimental studies carried on.

As one approximation, at an average 50% continuous load 12 hrs. daily (or 25% for 24 hrs. daily), energy consumption would amount to 1800 KW hrs./day or 54,000 KW hrs./month. Applying the Savannah Electric & Power Co. rate schedule for energy consumption (given in the section on prefabricated facilities) without the long hours use charge the cost of energy would be \$872./month (2500 KW hrs. @ 1.9¢ and 51,500 KW hrs. @ 1.6¢); As with similar calculations for other facilities, the high-rate brackets for the 1st 2500

KW hrs. in the rate schedules has been bypassed since this facility is part of an over-all larger facility.

Temperature Control. The 4 walls and the ceiling of each room are surrounded by an annular controlled air space. Temperature control in the chamber can be achieved either (1) by circulating air through the annular space without admitting it into the room, or (2) by also admitting it into the room through automatically controlled recessed dampers in the ceiling, with exhaust through wall grillage at floor level. The air temperature can be varied from -30° F to plus 130° F. (3) The floor can be conductively heated and the room space radiantly heated by a liquid-carrying pipe system buried in the concrete floor of each room. The temperature range of the brine used in this system is from -30° F to plus 130° F.

Relative Humidity Control. It is stated that through the joint action of temperature variation, humidification and dehumidification of the influent air, and water spray nozzles in the ceiling, relative humidity can be varied over a range of 25% to 100%. Very precise control of temperature can be obtained at all levels and of relative humidity between 25% and 90% over the temperature range of plus 30° to 130° F.

Air Movement. Air movement in the chamber is considered ancillary to temperature and relative humidity control, i.e., it is an element of the air conditioning system rather than an independent variable.

The turbulent air flow rate can be varied from 0 to 10,000 cfm. This maximum air flow rate applied to one of the main chambers (about 2650 ft³) represents a gross air change rate of around 4 air changes/min⁻¹ and a gross downward velocity rate of around 0.5 fps.

Artificial Lighting. Artificial light control beyond "normal" interior lighting levels has not been attempted at this laboratory. A series of pyrheliometer readings of ambient light values in the Purdue area has been made, with great variability in results due to air mass, cloud and fog cover conditions. Considerable uncertainty remains as to what light intensity, quality and programming are desired.

Other Climate Controls. Under proper temperature conditions in the chambers, the humidifying spray nozzles in the ceiling can accurately simulate rain, sleet and fog conditions in the rooms and produce snow - ice.

Mechanical Room. Equipment in the mechanical room is complex and expensive by comparison with other climate control facilities visited. This is due to a number of factors, among which are the substantial total cubage of the two environmental control chambers, the very low temperatures which can be reached and, presumably, the sophisticated type of humidity control equipment.

The refrigeration and heating phases of the mechanical room for the two chambers include three two-stage compressor systems of 300 HP capacity, and hot and cold brine systems, each with brine storage tanks. The hot brine is heated by steam to a maximum temperature of plus 180° F and the cold brine can be chilled to -30° F.

The hot and cold brine can be mixed for temperature adjustment.

Humidity control equipment consists of two Kathabars in series (one very large and one of medium size), which use the lithium chloride method and are known to have highly sensitive control characteristics.

General Comment. The Purdue facility materially exceeds in temperature range, sophistication and cost any of the other climate control facilities visited. In temperature range it is known to be surpassed only by ERDL test chambers at Ft. Belvoir, Virginia, where a 14 x 32 heavy equipment chamber can be operated at -85° F to plus 165° F.

Facility: Agricultural Research Center, Monsanto Chemical Company.
Location: 800 N. Lindbergh Blvd., St. Louis 66, Mo. (About 10 miles west of the city).
Contact: Dr. Clyde Wilson.
Age of facility: About 3 years.
Date visited: December 14, 1960.

GENERAL DESCRIPTION OF FACILITY

This facility consists of a large modern laboratory building which contains, in addition to other room space, two types of controlled environment facilities. One type consists of two insectary rooms with temperature and relative humidity control but no other variables. These two rooms are not further considered in these notes.

The other type consists of four "growth" rooms with temperature, relative humidity and artificial light controls; air movement as an element of air-conditioning also is subject to control. Each room is 8 ft. by 7.5 ft. by 7 ft. high. The controls of each room are set for 4 different temperature conditions. Three rooms are provided with relative humidity control, one with none. Artificial lighting capacity is the same for each room.

There are no published references with a physical description of these facilities beyond a short picture story in *Electrified Industry*, Sept. 1960, p. 29.

The primary purpose of these rooms is to grow terrestrial plant life, including molds and fungi, under artificial conditions approximating those in nature, in order that the effects of agricultural and mold-control chemicals can be tested on specimens developed in the growth rooms.

The steam and chilled water supply equipment in the mechanical room is common to all four "growth" rooms and to the two small insectary rooms, but separate from related equipment for the rest of the building. Each room has its own individual temperature and humidity control unit, served by the central supply system.

DETAILS OF GROWTH ROOMS

Cost of Construction. The controlled environment facilities were built on a lump sum contract for the entire building and their exact cost of construction is not known. The construction cost was roughly estimated by my contact at \$50,000, of which \$10,000 represents the cost of the two insectary rooms and \$40,000 represents the cost

of the four growth rooms, including the mechanical equipment but not the general purpose mechanical room structure or mechanical room utilities services. The approximate unit growth room construction costs are \$165 per square foot and \$24 per cubic foot.

Operating Costs. One maintenance engineer spends approximately 5% of his time with the equipment pertinent to these rooms.

Repair and Maintenance - Maintenance of the recorders is included as a small part of an overall maintenance contract covering all the buildings. All light bulbs are replaced once a year.

The electric costs are not separated from the rest of the building.

The light bulbs operate an average of 14 hours per day while the 25 HP compressor and the 6-1/2 HP auxiliary motors all operate continuously. (Note - compressor probably operates on and off on a continuous service basis).

General Features. The growth rooms are plain rooms without built-in equipment except for the environmental controls and cold water tap and electrical outlets. They have stainless steel walls and stainless steel walk-in refrigerator entrance doors. The floors are provided with steel duckboard type grillages (4" channel irons), which support the plant tables, and also serve as air inlets and drainage outlets.

Artificial Lighting. Each growth room is provided with 40 200-watt Sylvania Very High Output Type (VHO), fluorescent lamps, each 96 inches long. These lamps are supplemented by 20 100-watt incandescent lamps. The total wattage is accordingly 10 KW/room or 40 KW for the 4 rooms. The light bank is mounted in the ceiling, is separated from the rest of the growth room space by plate glass and a forced air draft is passed through the light bank and between the lamps and plate glass for cooling. No water barrier is needed due to the low wattage of the fluorescent lamps.

The ballasts required for the fluorescent lamps are located in another room in a bank along the partition wall and at ceiling height. By so doing, the small additional heat generated by the ballasts is eliminated as a growth room removal problem.

The fluorescent-incandescent lamp banks system was stated to provide about 2500 to 3000 ft.-c. of photo intensity at the prevailing plant growth levels. This was said to be about one-third of intense summer daylight in the St. Louis area.

Temperature and Relative Humidity Control Systems. The temperature control system was reported to have a sensitivity range of plus or minus 2° F for the temperature range involved; that of the relative humidity control system as plus or minus 2 or 3% within its range.

The first growth room can be operated at a temperature range 50° to 70° F, that of the second @ 70° to 90° F, that of the third @ 80° to 100° F and that of the fourth @ 90° to 120° F. The temperature ranges can be extended beyond these nominal ranges but likely at the expense of the RH control range.

The first growth room has no relative humidity control, all others can be operated over a 50 to 98% range.

Since these are plant growth rooms, the operating ranges and sensitivity of control of the air mass in the rooms is significant only at plant growth elevations; it is not presumed for example that, in these and other similar growth rooms visited, the temperature and relative humidity of the moving air immediately under the plate glass of the lamp banks meets the control standards cited.

Air Movement. As an element of temperature and relative humidity control, influent air is supplied at floor level through the duckboard floor system and is exhausted through a single wall grate near the ceiling. The maximum air change rate is high (2 changes per min.).

The air-conditioning system is essentially a closed system but up to 10% outside air can be admitted.

Mechanical Room. The general purpose mechanical room which serves the entire building is about 30 ft. by 40 ft. in plan dimension and is jammed with mechanical equipment. Air-conditioning for the general building space is served by a 100 HP compressor, that for the 4 growth rooms by a 25 HP compressor.

Temperature adjustment of the air is accomplished by conventional chilled water air-conditioning equipment. Humidification is accomplished by adding steam to the air flow in the air-conditioning plenum chamber. Dehumidification is achieved by controlled chilled water cooling below the dew point, followed by reheat to the temperature setting. Since very little outside air is admitted, no equipment for heat exchange between waste air and fresh air is provided.

GENERAL COMMENTS

It was stated that the facility had undergone many minor modifications since the original design:

1. Increased the number of lamps in each room.
2. Redesigning the light chamber for more efficient cooling of the lights.
3. Increased the cooling coil and fan capacity in the unit controlling the air in the light chambers.
4. Added another 2 HP fan to move air through the light chambers.
5. Relocated the ballasts for better cooling and accessibility.
6. Increased the pressure in the steam line to increase the humidification capacity.

and it is planned to increase the size of the steam (reheat) coils in the room units to bring them more in line with the capacity of the cooling coils.

Further modifications are contemplated.

Most of the common agronomic United States crops including cotton, corn, wheat and other cereals and grasses plus many common weed species have been grown in these rooms with very good success. They have found, however, that if it is attempted to grow some plants such as soybeans and buckwheat at temperatures above their optimal, the light intensity may become deficient.

The problem of inferior design as a result of placing the design of controlled environment facilities in the hands of a non-specialist responsible for an over-all building facility was repeatedly encountered during my tour. Design of the controlled environment element and its equipment is commonly assigned to mechanical and electrical engineers who are experienced in the design of climate control and lighting facilities for office and industrial buildings, but not for controlled environment facilities of the type involved in this survey.

Facility: Department of Biology, Emory University.

Location: Atlanta 22, Georgia (six miles northeast of the center of the city).

Contact: Dr. Robert B. Platt, Professor of Biology.

Age of facility: Present facility dates from November 1956.

Date visited: December 22, 1960.

GENERAL DESCRIPTION OF FACILITY

This facility consists of a small plant growth room located in the basement of the Biology Building on the Emory University campus. Its operation is under Dr. Platt.

The environmental controls are artificial light irradiation, temperature and relative humidity. The lighting system is high-intensity.

The growth room is 1.4 m. wide, 1 m. deep and 1.1 m. high. The area is 15.1 ft.² and the volume is 54.5 ft.³.

Some details of the growth rooms and also the basis for the artificial irradiation design are given in an article by Dr. Platt (29).

DETAILED DESCRIPTION OF FACILITY

Construction Cost. Dr. Platt estimates the construction cost on a contract basis would be about \$10,000. The actual cost to Emory University of this particular growth room was an unknown lesser amount because much of the fabrication and installation work was done by the University staff.

Operating Costs. During the 4 years the facility has been operated, no mechanical repairs have been needed. There is no paid operator. Operating costs accordingly are confined to lamp replacement and the electric energy required for the lamps and mechanical equipment.

The 36 lamps were estimated to cost about \$2 each and to have a life of 600-800 hours. Based on an average life of 700 hrs. and 10 hrs. average daily operation, the lamp life is about 2-1/3 months and the lamp replacement cost amounts to about \$360 per year, if the facility is used continuously.

Electric energy requirements consist of a 10.8 KW lamp load plus a 750 watt heater and a 1 HP compressor motor which operate on an on-off basis. In the following calculation of energy costs, the 2 on-off units are assumed to operate 50% of the time on an annual basis and an applicable tariff schedule of the Savannah Electric and Power Co. is used for unit energy costs.

Av. Monthly Energy Use	KW Hours
Lamps	3240
Mechanical equipment	540
Total	3780
Energy Cost	
3780 KW hrs. @ 1.9¢	\$ 71.82
Long hours use charge (12.3 KW installed capacity)	
1320 KW hrs. @ 1¢	13.20
Demand charge - none	
Total/month	\$ 85.02
Total/day	2.83
Total/day/sq. ft.	0.19

Artificial Irradiation. After making a survey of available lamps, Dr. Platt selected G.E. R-40 300 watt reflector spotlights. These are installed in a bank of 36 lamps 1.3 m. above the floor of the plant growth chamber. This is a tungsten filament incandescent lamp. An interesting feature is the method of lamp mounting. The receptacle of each lamp is mounted on a ball and socket joint. This in turn is clamped to a frame to form a square grid with the receptacles in 15 cm centers. The lamps are 2.5 cm. apart on an edge to edge basis. In a vertical position, the overlapping intensity patterns of the lamp bank vary from 12,000 ft. candles in the center of the grid at growth chamber floor level to 8,500 in the outer portion. However, by slightly angling the lamps on their ball and socket joints almost uniform illumination can be provided at floor level.

Dr. Platt stressed the importance of approximately full sunlight intensity for experimental studies of plants having high light intensity requirements. In his article (29), he points out that summer sunlight intensities at noon on relatively clear days range from around 9,000 to 14,000 ft. candles, depending on time of year, altitude, latitude and sky conditions. In contrast, he notes that "Conventional plant growth chambers utilize primarily fluorescent lamps which produce a maximum illumination of only 2000-2500 ft. candles". In this connection, it was noted that the type of plant whose growth he is presently studying is a small succulent type plant which is found in nature in small patches of soil on granite hillsides where there is no canopy growth.

The particular lamp selected for this growth chamber is stated to have an emissivity of 3500 lumens/lamp and a nominal beam spread of 30°. The cited article mentions that the only other theoretically suitable lamps of other types which were located for this high-intensity installation were mercury types such as the GE BH-6 1000-watt lamp of 65,000 lumens, used for searchlights and the GE AH-9 3000-watt lamp of 120,000 lumens, used for high-bay lighting. Reasons for not using these lamps are given in the article.

Because high-intensity filament type lighting is employed, it is necessary to separate the overhead lamp bank from the rest of the chamber with a circulating water bath on a tempered plate glass base. The plate glass base is L-O-F-Tuflex, 1/4 inch thick. It is said to have 4 times

the resistance to thermoshock and 3 to 5 times the resistance to impact shock of ordinary plate glass. This glass is stated to have 90 to 93% transmission in the visible spectrum, with a cut-off between 3100 and 3600 Angstrom units and a slow fall beyond 10,000 A. (Note: Glass in the lamp bulbs also has a high degree of u.v. filtering power).

The lamp bank is also air-cooled by a 1/3 HP exhaust fan. The circulating water bath is admitted through a small perforated pipe along one side of a 6 inch high metal box holding the plate glass base and the water above it. The depth of water in the frame is controlled by 2 levels of outlet orifice holes in the opposite side of the metal box. By increasing the water inflow rate, the water level can be raised above the lower holes up to the upper level holes. The heights of the 2 levels of orifice holes above the plate glass base are 5 and 10 cm.

The article gives interesting data on the filtering characteristics of water. From the values cited, it is obvious that these filtering characteristics are related to depth of water by non-uniform factors for given wave length ranges. Values cited in the article are:

Filtering Power of Water

Depth of Clear Water	<u>Wave Length Range - Angstrom Units</u>	
	2,000 to 6,000	6,000 to 30,000
1 cm	0.01%	26.9 %
10 cm	0.08%	45. %
100 cm	7.5 %	63.34%

It is also stated that 10 cm of water in the water bath reduces the heat radiation from this lamp bank to a level comparable to that received from the sun. At 1.3 m. from the source, radiation received is 1.1 g-cal per square centimeter per minute, while at 0.9 m. it is increased to a value of 1.65.

Temperature and Relative Humidity Controls. Control equipment mounted on the outside of the growth chamber with appropriate sensing elements extending into the chamber consists of a Foxboro recording temperature and dewpoint controller near the top of the chamber and a program timer. The lamps are operated continuously and at a steady intensity rate during the day-length light exposure period ranging from 8 to 12 hours.

Mechanical Equipment. Due to the small size of the growth chamber and of the mechanical equipment (750 watt heating unit and a 1 HP compressor motor), there is no mechanical room, the equipment in the form of package units being mounted on the side of the chamber. Also, due to the small size of the facility, recirculation of air and water is not carried out. The water consumption rate is about 0.5 gpm while the lights are on.

The sensitivity of control of the air temperature and relative humidity in the chamber is about plus or minus 2%. The temperature range capability is from 40° to 100° F and the relative humidity range is from 15 to 90%. The relative humidity control equipment is a Foxboro lithium chloride system. This is supplemented by an atomizing nozzle in a wall of the chamber which utilizes compressed air at 30 psi. Both the 750 watt heater and the conventional 1 HP refrigeration unit use a fan for forced air circulation into the chamber. The article by Dr. Platt states: "For most uses, humidity control may not be necessary because of transevaporation, which occurs naturally within the chamber."

Operating Problems. No operating problems were reported. The limited sensitivity of adjustment which can be obtained with a non-recirculating air-conditioning system, especially for low and high temperatures and humidities indicates need for a recirculating system where more precise control is required (29).

Facility: Agricultural Research Service, plant growth rooms at Plant Industry Station.
Location: Beltsville, Maryland. (Address Crops Research Division, ARS, U.S. Dept. of Agriculture).
Contacts: Dr. H. A. Borthwick; and Dr. Robert J. Downs, plant physiologist.
Date visited: January 30, 1961.

GENERAL DESCRIPTION OF FACILITY

The ARS Plant Industry Station has an unknown number of plant growth rooms. Three of them were selected by Dr. Downs as having either points of special interest to me or of providing a representative cross-section of the facilities at Beltsville.

These three rooms had certain characteristics in common. They were all about the same size (9 ft. by 18 to 20 ft.); they all had the same environmental controls (temperature and artificial irradiation), although these varied in detail. None had controlled relative humidity. Cooling equipment for all three rooms was served by central system recirculating refrigerant lines (ethylene glycol refrigerant), which serves 6 growth rooms. They all have semi-gloss white walls that are made diffuse by float plaster surface.

DETAILED DESCRIPTION OF GROWTH ROOMS

Room No. 1. Room No. 1 was shown because it has an original carbon arc lamp used in the first growth room established at Beltsville back in the 1930's. This particular type of carbon arc lamp was developed for use in hospital facilities for ultra-violet ray treatment of patients.

This lamp has 2 pairs of electrodes. Each pair is so positioned that as the electrodes in one circuit become worn, the other pair automatically takes over. By a sequence of alternate operation, the electrodes can give continuous light for 8 hours.

The lamp is rated at 60 volts, 75 amps., and uses alternating current. It provides 3000 ft. candles at plant level and is supplemented by 8 200-W. 230-V. incandescent lamps which provide 300 ft.-c. at plant level.

The room has a refrigerant coil and a blower for cooling. It is a recirculating system with the fan operating continuously and the solenoid

controlled coil intermittently. Due to the heat emission of the lamps, there is no need for heating.

Room No. 2. This room is equipped with an overhead bank of T-8 slimline cool white fluorescent lamps, supplemented by about 10% incandescent irradiation on a foot-candle basis. The combined value at plant bench level is 1600 ft.-c. of irradiation. The distance from lamp bank to plant bench level is 1.3 m. in both Rooms 2 and 3. This probably provides a distance of around 1.0 m. from lamp bank to plant under most growing conditions. The lamp bulbs are directly exposed to the air of the room in Rooms 2 and 3. The plant bench area is slightly smaller than the lamp bank area in these rooms to avoid lowered irradiation values for plants along the edge and to provide a walkway in the least desirable part of the room.

The fluorescent lamps are rated at 90W, and there are 106 of them. There are also 42 100-watt incandescent lamps. Ballasts are outside of the conditioned space. Exclusive of ballast losses, the energy input capacity of the lamps is 13.74 KW and, on a basis of an annual average light-up period of 10 hrs. daily, the net electric energy consumption would be 137 KW/operating day.

Except for the unascertained cooling load on the central station refrigeration equipment, the lamps for all practical purposes are the only electric energy load imposed by this room.

This room is cooled by conditioned air which enters the room through a peripheral duct immediately below the lamp bank, with a downward draft to a floor level exhaust.

Room No. 3. This plant growth room was of principal interest because it is the newest at the station. The plant benches were conventional in design and similar to those in Room 2. It is characterized by two improvements over the features of Room 2. One is the air cooling system. The height to the lamp banks is 8 feet, and

above these banks is an adjustable slot-type false ceiling. Above this is an air plenum chamber which uses an additional 6 feet. A small part of the air enters the room through the lamp banks, and passes out through a floor level exhaust. As a result of cooling the lamps there is about a 10 degree temperature rise for which allowance is made of course by the room thermostat and by the flow control of the air cooling coil. The greater part of the air enters the growing area through vents and deflectors along the sides of the room. The deflectors aim the air across the bench so that plants in the center receive the same air flow as those on the edges.

The other improvement is in the lighting system. The fluorescent lamps are served by chokes and condensers rather than by ballasts. This gives a 10% higher over-all efficiency and greatly simplifies the wiring system between the choke system and the lamp banks. Two lamps are served by each choke. The power supply for the fluorescent lamp is 600 volts and for the incandescent lamps 120 volts.

The fluorescent lamp system consists of 64 Power-Groove lamps, 96 inches long and rated at 215 watts. The lamp banks cover an area 8 ft. by 16 ft. The lamps are mounted in pre-wired, aluminum frame modules, with 8 lamps per module. The modules are made by a firm in Cleveland which specializes in their fabrication. There are also 40 100-W incandescent lamps. The gross electric energy load of the 2 lamp systems is 21 KW and the energy consumption over a 10 hr. day accordingly is 210 KW hrs. This represents a monthly operating cost of \$108 on the kilowatt hour schedule and \$21 on the long hours schedule (total \$129) of the Savannah Electric and Power Co. As in other cost calculations made in this series of notes the rate steps used are after deducting the first 2500 KW hrs. in the rate schedule on the grounds that the growth room is an increment of a comprehensive electric energy-using facility.

The temperature range used is very limited because the only temperature desired is one which will cause an optimum growth rate for the temperate climate plants grown. While the lamp banks are operating the temperature is kept at 70° F about 90% of the time. At other times it may run from 60° to 80° F.

One minor disadvantage of using the room air supply to cool the lamp banks, or conversely

not having a separate cooling system for the lamps, is that the air change rate must be stepped-up to avoid overheating the room. The air inflow rate in Room 3 is about 3400 cfm and the over-all room volume including the space above the lamp banks is 2268 ft.³ (9 ft x 18 ft x 14 ft). There are accordingly 1.5 gross air changes per minute. Although Dr. Downs considers this to be somewhat higher than needed, it is many times that of some other growth rooms visited.

Construction Cost. The construction cost of Room 3 is not precisely known because the work was performed on force account by the Station staff. However, Dr. Downs estimated the approximate cost as \$12,000 exclusive of the Freon compressors. The cost of Room 2 is believed to be in the same general order. It is perhaps somewhat higher due to the more complicated lamp bank wiring.

This low cost compared with that of other plant growth rooms of comparable size which were seen at other locations is attributed to simplicity of general design and the fact that some mechanical equipment costs are not included. (The lamp banks are not separated from the rest of the room by a heat filter, there is no separate air supply to cool them, the cost of wiring has been kept down and there is no relative humidity control). These factors not only lessen the cost of the growth room per se, but tend to make the over-all cost modest due to the relatively simple mechanical equipment needed to serve it.

GENERAL DISCUSSION

This visit was of special interest because the Plant Industry Station has been operating plant growth rooms for about 25 years and its plant scientists have had long experience and have established reputations in this field. The general impression gained was that the facilities there were much simpler than at some others visited.

In the matter of light intensity, the Beltsville facilities are in the low-intensity category. When inquiry was made as to the reason why the ARS facility at Watkinsville, Ga., in contrast, employed such high intensity lighting, it was pointed out that at Watkinsville the interest was in studying plant water loss and water demand requirements and that this called for a high level of irradiation as one parameter. This is in the

interest of thermal effects; it is not considered that the bean plants grown at Watkinsville require such a high level for photo-biological processes.

In this connection, Dr. Downs stated that he could grow beans better in a growth room at 1600 ft.-candles than in a greenhouse under solar irradiation. (Note: The highest irradiation level in a greenhouse probably would be 10,000 to 12,000 ft.-c. less filtration loss. Over the total energy wave band this loss probably amounts to about 40% but is probably less than this in the visible spectrum of which the ft.-c. is a unit of measurement). The more favorable growth rate at 1600 ft.-c. was attributed to the fact that the plants received more or less all the irradiation they could utilize for photo-biological processes and received this saturation value more hours per day and more days per week. Constant favorable temperature is also important.

In discussing the light intensity needed for an aquatic plant growth room, such as for algae, although Dr. Downs had not grown algae he doubted if it would be necessary to use a high-intensity incandescent lamp system for this purpose in order to overcome the light-filtering effect of water in a test model intended to simulate the full water depth range of algal growth in nature.

To a large extent this was because improvements in the design of fluorescent lamps now permit reaching a value of as high as 7,000 ft.-c. in a plant growth room, if desired. This could be achieved by a massed bank of small diameter

V.H.O. (very-high-output) fluorescent lamps served at a stepped-up frequency. The frequency changer would have the added advantage of making light programming easy if programming should be desired. By varying frequency, dimming could be achieved on a time cycle over a range of full intensity to zero.

Dr. Downs stated that previous objections to Power-Groove fluorescent lamps on grounds of difficulty of calibration had been solved by new lamps of this type and that use of Power Groove tubes with their relatively high output was a method toward achieving high-intensity values.

It was stated that one way to lower construction and operating costs at Beltsville would be by reducing the size of the plant growth rooms. For the type of studies carried out there, the room size could be cut in half. (Their studies do not require separate plant benches served by different irradiation values in the same room.)

Although it had been found that some plants exposed to fluorescent lamps required exposure to supplementary incandescent lamps for normal growth patterns, the 10% supplementation value so commonly used was not necessarily the minimum satisfactory value, it is only known that it is enough. (In this connection, Went⁽²⁵⁾ in studies with tomato plants reports a maximum effect with 5 to 10% supplementation.) It was further stated that some plants grew better without any incandescent lamps.

Facility: Southwest Water Conservation Laboratory, Agricultural Research Service, U. S. Dept. of Agriculture.
Location: Box 816-A, Route 2, Tempe, Arizona (outskirts of Phoenix, Arizona).
Contact: Mr. Lloyd E. Myers, Director.
Date visited: December 19, 1960.

FUNCTIONAL PURPOSE OF FACILITY

This field station in its use of its controlled environment facility is concerned with the use of water by plants, i.e. studying the effect of environmental factors on the uptake, translocation and transpiration of water by the plant system.

GENERAL DESCRIPTION OF FACILITY

This controlled environment facility consists of a single growth room 9 ft. by 20 ft. by 12 ft. high. The net height from floor level to a Mylar plastic ceiling partition is 9 ft. The light banks are in the partitioned-off ceiling space.

The environmental controls are: artificial irradiation, temperature and relative humidity. Air movement is controlled only as an element of the air-conditioning system for temperature and relative humidity control.

The walls are finished with flat white paint on a plaster with a special aggregate intended to resist high humidities. The ceiling is 8 mil Mylar plastic with good radiation transmission properties. The floor is concrete and the entire room space is free of any protruding built-in equipment. There are two movable steel plant benches each about 3 ft. high and about 30 inches wide which extend over practically the full length of the room (20 ft.). The area of the room is 180 ft.² and the volume below the ceiling partition is 1620 ft.³. The volume including the light bank space is 2160 ft.³.

A unique feature is that, due to the favorable climate, the mechanical equipment serving the growth room is unhoused. This equipment is in the form of outdoor package units.

Although the growth room was completed over a year ago, it is not in operation due to the fact that the controls have not yet been "checked-out" by the manufacturer (Minneapolis-Honeywell). A similar type of delay in instrumentation was encountered at the Climatron in St. Louis, although the Climatron is operating.

The probable future operating pattern will be to vary all three of the environmental controls (temperature, relative humidity and irradiation), but at different times. That is, two will be kept constant and one varied at any one time. Another possibility is that all three variables will be held constant at any one time, with a fourth independent variable introduced, such as varying the temperature of a nutrient solution in water-plant growth jars as an index of soil temperature conditions in nature, with room air and light conditions held constant.

The range of the environmental controls at this facility are:

Temperature - 4°C to 40°C (39°F to 104°F)
Irradiation - 0 to 3500 ft. candles
Relative humidity - 5% to 95%

The entire laboratory building in which the controlled environment facility is housed and the facility itself were constructed under the super-

vision of the General Services Administration (GSA) and there is a complete set of plans and specifications for the installation as planned prior to the many modifications which were made during the course of construction. There are no "as-built" plans.

DETAILED DESCRIPTION OF FACILITY

Construction Cost. The exact construction cost of the growth room and appurtenant mechanical equipment is not known because these were built as elements of the over-all laboratory building, which was on lump-sum contract. The total cost of the over-all facility was \$400,000 for 11,000 ft.² of single story brick construction (\$36 per square foot).

Mr. Myers estimates that the growth room facility cost not less than \$50,000 but that this figure would be low if it were to be replicated because of unusually fortuitous circumstances. A safer figure probably would be \$60,000 plus the cost of a mechanical room structure and ENR construction cost adjustment if erected at Cincinnati.

Operating Cost. Adequate data on operating costs are not available because the growth room has not been placed in operation.

There is one full time maintenance man for the entire laboratory but proration of his time is not possible at this stage. The need for repairs, replacements and modifications is definite but unpredictable.

Energy costs might be approximated on the following basis:

The lamps will operate a maximum of 12 hours.

A 10 HP compressor for lamp cooling also would operate a maximum of 12 hours only, possibly 50% of the time within this period.

A 15 HP compressor for air-conditioning might operate at one-third of full load continuous duty over the 24 hr. period, but the operating cycle obviously will vary with season of year.

Supplementary motors in the climate control equipment, aggregating about 5 HP might operate practically full time over the 24 hr. period.

The average monthly heating bill (natural gas), prorated over the year for the 180 ft.² of insulated

growth room space should be negligible in the Phoenix, Arizona, climate.

Artificial Irradiation. The type of artificial irradiation is primarily fluorescent, supplemented by a small quantity of incandescent filament lighting.

The fluorescent lamps are daylight type (96 inch, T-17, 200 watt, 13,000 nominal lumen rapid start type). There is an overhead light bank of 5 panels which occupies essentially all of the ceiling space. The 5 plastic sheet panels are removable for access to the lamps. There are 28 fluorescent lamps in each panel, or 140 in the room. These horizontal lamps are in two staggered rows with one row several inches above the other. In this way the lamps can be spaced to provide a solid field of overhead light (i.e. the projected edges of each lamp tube in the upper row are common to the edges of two adjoining lamp tubes in the lower row).

The supplementary incandescent lamps are concealed and are located above the two rows of fluorescent lamps. As a result, the incandescent irradiation must either pass through or bend around the fluorescent tubes. There are eight incandescent lamps of 300 watts each, totalling 2400 watts in the room.

Because of the low heat emission from the predominating fluorescent lamps a circulating water bath between the light sources and the plant room is not needed. Cooling is provided by circulated cool air in the light bank space, supplied by a freon refrigerating system with a 10 HP compressor.

One design factor noted is the loss of light intensity with age in fluorescent lamps. Subsequent reference to a General Electric lamp catalog indicates that fluorescent lamps are rated on a basis of their lumen output after 100 hours' use, due to the rapid drop in efficiency during the first 100 hours. The light output during life (6000 to 7500 hours), averages about 85% of the 100-hour value with a terminal point of about 80% of the 100-hour value for the lamp size and type under discussion. Lamp efficiency also varies with type of phosphor, lamp length and diameter, bulb wall temperature and energy frequency.

A noteworthy feature of the fluorescent lamp circuit is the provision of a frequency changer. By increasing the frequency from 60 cycles to 360 cycles, various benefits are obtained. The

visible stroboscopic effect is eliminated and some plant researchers are of the opinion that elimination of this effect may favor plant growth. Other advantages as cited in a G.E. lamp bulletin are moderate increase in illuminating efficiency, use of simpler and smaller ballasts (50% reduction in size and weight), increased ballast efficiency and simplification of instant starting circuits. To insure proper operation, the frequency changer requires a separate supply line transformer because of its sensitivity to voltage drop.

GSA specifications for the growth room frequency changer called for a magnetic type changer to convert 3 phase, 60 cycle current with a nominal output voltage of 480 volts to an output current of 600 watts, 360 cycle single phase and an efficiency of not less than 75%. The power output rating of the frequency changer is 25 KW, representing the maximum demand of the fluorescent lamp circuit and ballasts.

The ballast system consists of one capacitor type ballast for each two lamps.

Temperature and Relative Humidity Control. Although data were prepared on the sensitivity (tolerance) of the temperature and relative humidity controls, these were not included in the GSA specifications, which dealt only in ranges and capacities.

The outside climate design conditions specified by GSA were: Winter 30° F, 50% Rh; summer 107° F, 39% Rh.

The GSA specifications listed two sets of desired room conditions. Condition A was for a fixed relative humidity of 90% to be maintained while the room air undergoes a temperature change from 41° F to 104° F. Condition B was for the room to be operated for extended time periods at any selected point between 68° F and 104° F with the relative humidity at any selected point between 5% and 95%. All temperatures cited are dry bulb.

Specifications for the dehumidifier called for an automatic dry chemical absorber type (activated alumina specified), with reactivation by a natural gas furnace. The capacity specified was removal of 700 grains per minute of moisture from 700 cfm of air, to operate over an air temperature range of 25° F to 60° F and to be able to reduce the moisture content over this range from 15 grains to 1.9 grains per pound of air.

The dehumidifying unit actually installed consists of a silica gel rotating disc type with 180° exposure to the air supply and 180° exposure to the reactivating heat.

Air Movement. The GSA specifications called for 10 air changes per hour with "air motion to be held as low as possible."

Control Room. A control room about 10 ft. by 20 ft. by 10 ft. high adjoins the growth room. Most of the space in this control room was made necessary by the absence of a mechanical room building since it is mainly occupied by a plenum chamber in the air-conditioning system for air-mixing. Other control room equipment includes a relative humidity control panel, a magnetic frequency multiplier and banks of solenoids for the lamps. The bank of ballasts is inside the growth room in the lamp bank area. These are commonly placed outside the growth room because they produce some heat and do not need to be located in the same room as the lamps.

The plenum chamber in addition to its air mixing facilities, has a refrigerating coil, a re-heat coil, a steam humidifier, a fresh air intake and an air connection to the outside chemical drier.

INCIDENTAL FACILITIES

In addition to its growth room the laboratory has 3 constant temperature rooms, each 20 ft. long by 9 ft. wide. These rooms do not have any variable environmental controls other than temperature. The air-conditioning equipment serving them is independent of the growth room equipment. They are operated at 3 different temperature ranges:

Room No.	Temperature range
1	28.4° F to 68° F
2	30 to 86
3	68 to 104

Because of their lack of significance in this study, no further information was obtained on these rooms.

DESIGN AND CONSTRUCTION PROBLEMS

This facility has had many problems in design and construction. These have arisen in part because design of the specialized features has

been left in the hands of the general architect, without any requirement for consultation with design specialists who would be more likely to interpret the needs of the facility as a research unit. For example, the detailed design of growth room equipment may have been turned over to mechanical and electrical engineers competent in the design of air-conditioning and electrical systems for office and industrial buildings but who are not familiar with the requirements of specialized research facilities.

Compounding the problem is the fact that controlled environment facilities are not sufficiently standardized from a standpoint of research results and research operating conditions for the requesting agency to be able to clearly define its needs within the practical limits of the art and within reasonable construction and operating costs, operating dependability and simplicity considerations.

Another factor in the problems of the Phoenix facility was the lack of time involved in final design. The growth room was an element of a larger facility and the larger facility had a "time" deadline for several reasons.

An added design problem which has recently developed is that the refrigeration system is not adequate to cope with the heat emitted by the frequency changer, which has a specific temperature ceiling for satisfactory operation. Provision of added refrigeration capacity to serve the room containing the frequency changer is necessary.

OTHER FACILITIES PLANNED

The Southwest Water Conservation Laboratory is an element of the Western Soil and Water Management Research Branch. This in turn is in the Soil and Water Conservation Division of the Agricultural Research Service (ARS).

The Branch has been developing a long range preliminary plan for a "total climate control" facility. It is a wind tunnel with artificial irradiation and presumably temperature and relative humidity control. Whether it has provision for altitude variation is not known. The preliminary design is based partly on a wind tunnel at Ft. Collins, Colo. The present estimated cost is in the order of \$2 million, an important part of which may be due to the very large volume of conditioned air required under high wind velocity conditions.

Commercially Produced Prefabricated Controlled Environment Facilities

Commercially produced prefabricated controlled environment facilities appear to be of two main types: (1) altitude chambers, and (2) plant growth rooms. Facilities in the first category cover more variables and function over a broader range than the plant growth room units.

Three companies are known to produce altitude chambers along with other controlled environmental variables. They are:

Tenney Engineering Co., 1090 Springfield Rd.,
Union, N. J.
Guardite Co., P. O. Box 188, Wheeling Ill.
Vacudyne Corp., 14419 So. Torrence Ave.,
Chicago 33, Ill.

Commercial prefabricated plant growth room facilities are known to be sold by two companies:

Percival Refrigeration and Manufacturing
Co., Boone, Iowa
Labline Inc., 3072 W. Grand Ave., Chicago, Ill.

TENNEY ENVIRONMENTAL EQUIPMENT

The Tenney Engineering Co. makes six principal lines of controlled environment chambers and cabinets as well as other specialized test cabinets. These are:

1. TenneyZphere chambers for combined testing of altitude, temperature, humidity, ram air and vibration.

Manufacturers cited standard performance features:

Altitude to 80,000 - 125,000 - 150,000 or 200,000 ft.

Low temperature: -80°F, -100°F or -120°F.

High temperature: Plus 240°F to Plus 350°F.

Relative humidity: 20% to 95% (Limited by a 35°F min. dewpoint and a 185°F max. dewpoint. 5% Rh capability at 160°F.

Dissipation of 350 to 2000 watts at low temperature.

Pre-set controls for programming. Standard sizes range from 24" x 24" x 18" to 48" x 60" x 96".

Rate of Pull-Down: From ambient temperature to -85°F in 2 hrs., -100°F in 2 to 2.5 hrs. and -120°F in 2 to 3 hrs.

Reheat Rate: Ambient to 200°F in 60 min.

Rate of Climb to 50,000 ft.: 5000 ft. per min.

2. Walk-in space chambers.

Variables: Altitude, ram air, rain, humidity, low and high temperature, vibration and solar radiation.

Sizes: Made to order -- no standard dimensions (One catalog cut shows a chamber 14 ft. by 14 ft. by 35 ft.).

Features: Altitude to 1.5 million ft. Temperature from -150°F to plus 2000°F.

Ram air flow and conditioned air as required. Pull-down and heat-up time in accordance with any specifications. Solar irradiation in a complete spectrum from 0 to 140 watts per square feet. Rainfall from 0.5" to 24" per hour.

Type of construction: Square cross section. Made of steel plates wrapped with I beams, spaced in proportion to altitude requirement.

Location of facilities: A back cover of the catalog shows chambers at the U. S. Navy Ordnance Station, Wright Air Development Command, Air Research Development Command, and General Electric.

3. Space simulators.

Small cylindrical cabinets with a 30" diameter by 30" depth work space.

4. Tenney-mite Strat.

Cabinets with a 14" cube work space.

5. Hi-low temperature test chambers.

These come in 3 sizes, the interior dimensions of which are:

19" x 20" x 48"

24" x 24" x 48"

37" x 26" x 48"

6. Sub-arctic industrial cabinets.

There are 27 sizes of these cabinets. They range from a 14" cube to 40" x 22" x 24".

Schedule A Schedule B

1 st 15 KW hrs.	1.35	
next 285 KW hrs. @ 4.9¢	13.96	
next 700 KW hrs. @ 4.4¢	30.80	
next 1500 KW hrs. @ 2.9¢	43.50	
next 128 KW hrs. @ 1.9¢	2.43	
2500 KW hrs. @ 1.9¢		\$ 47.50
128 KW hrs. @ 1.6¢		2.05
Long Hours Use Charge		
1128 KW hrs. @ 1¢	11.28	11.28
Totals	\$103.32	\$ 60.83

PERCIVAL PROGRAMMED PLANT GROWTH LABORATORY

This package-type growth room is 6 ft. by 9 ft. by 7.5 ft. in outside dimensions. The inside dimensions are the same, less the 4-5/8 inch thick insulated walls. The room is provided with temperature, air change and relative humidity control equipment and mixed fluorescent-incandescent filament lamps. Instrumentation includes three lamp clocks and one temperature clock to operate switches, two heater thermostats and two refrigeration thermostats. Optional instrumentation includes a humidity-sensing element (and a dehumidifier to go along with it), and a temperature and humidity recorder with a 7 day chart.

The quoted base price is \$5,000 FOB Boone, Iowa, and the estimated installation cost is \$600. Allowing \$100 for freight, the over-all cost without the optional equipment is \$5,700 or about \$133 per square foot and \$18 per cubic foot, based on outside dimensions. The recording equipment costs \$250 extra. The extra cost of the dehumidifier was not mentioned.

The power demand is 7.3 KW. This apparently includes the lights since the refrigeration equipment has only a 2 HP compressor. Operation of all of the equipment continuously 12 hrs/day at full load would require 2628 KW-hrs of electric energy/month.

Applying the general service schedule of the Savannah Electric and Power Co., the energy cost per month* would be:

*Schedule A is based on the growth room comprising the only load on the meter. Schedule B is based on the growth room as part of a pre-existing facility with the pre-existing elements using the first 2500 KW hrs. of electric energy.

Features of special interest are:

1. An aluminum roof is provided immediately above the lamp bank (1 inch above). This roof can reject up to 15,000 Btu/hr. from the growth room.

2. The brochure states that no heat filter is necessary or is provided between the lamp bank and the room space. This is because the lighting is mainly with fluorescent lamps and also because of the aluminum roof. The transmittal letter however, advises that a sectional barrier of Mylar tempered plastic is now provided as standard equipment. It is for use as a heat barrier and as a support for color filter films. The heat filter is intended for use without a water bath. Separate forced-air cooling for the lamp bank is provided.

3. Humidity control, with or without the optional dehumidifier can be accomplished as follows according to the brochure:

"Several adjustments can be made to influence relative humidity in the Lab without use of humidifying equipment. The frequency of refrigerator cycling and the introduction of outside air modify absolute humidity. Frequency of refrigeration cycling is influenced by the heat load which in turn may be varied by the number of lights in operation or use of auxillary heaters. Increasing the heat load therefore decreases the absolute humidity and lowers the relative humidity, while changing the temperature modifies only the relative humidity. Exchange with outside air affects absolute humidity by bringing in humid or dry, cold or warm air. If the air must be warmed to Lab temperature, the absolute humidity usually goes down, whereas if the entering air must be cooled, Lab humidity usually

increases. Lab moisture content is changed by evaporation and transpiration of plants. For this reason, relative humidity will be determined almost entirely by local conditions and not by design. Some additional humidity control can be achieved by using a humidifier and humidistat. Reliable data are not available on the necessity for controlling humidity to obtain optimum plant growth."

4. Insulation in the floor and walls is 3.5 inches of fiber glass.

5. The following specification features have been excerpted directly from the brochure.

Control of temperature: The Percival Programmed Plant Growth Lab provides an unusually wide range of temperatures - plus or minus 1°F from 45° to 95°F with full light-load. **Control of light:** Light intensity may be varied from 700 to 4,600 foot candles. Fluorescent and incandescent lights are controlled by separate time clocks for independent regulation of photo period. Alternate fluorescent lamps may be disconnected by a manually-operated switch for lower light intensities. **Control of day length:** Fluorescent light, incandescent light, and temperature are all individually adjustable. **Control of air exchange:** Fresh, filtered air is introduced as desired up to 12 complete changes of air per hour. **Control of humidity:** Humidity control is optional. Without humidity control, relative humidity varies from 75% to 90% with lights on, and from 90% to 100% with lights off. **Control of bench height:** Bench is raised or lowered by finger-tip control. Distance from lights can be varied from 15" to 79". This provides proper adjustment for either short or tall plants. **Control of leaf flutter:** Five blower coils, placed on two walls of the unit, bring in warm air from above the bench and discharge cool air below. It then rises gently up through the bench and back through the blower coils. There is no turbulence to cause leaf flutter.

Flexibility: The Percival Programmed Plant Growth Lab can be adjusted to reproduce climatic requirements from 45°F to 95°F, from 700 to 4,600 foot candles of light intensity, and any photo period desired, thus permitting a wide range of experiments. Controls may be instantly set to each experimenter's needs. This eliminates costly shut-downs.

LABLINE PLANT GROWTH ROOMS

This company has supplied detailed specifications on three models of plant growth rooms with the comment that they can be modified to meet the particular researcher's requirements. No prices were furnished. The company expressed an interest in trying to work out the specialized requirements of an aquatic plant growth chamber in consultation with some interested party.

No attempt is made here to fully abstract the three sets of specifications supplied. In brief, Models 840, 850 and 860 range in interior dimension from 51" x 26" x 38" high to 10 ft. x 6 ft. x 7 ft. high. They have temperature control in ranges varying from 20°F to 48°F minimum to 90 to 100° maximum, within limits of plus or minus 0.5° to 2°. Simulated solar irradiation is provided by fluorescent lamps, supplemented by incandescent filament lamps, at maximum levels of 1700 and 2000 ft. c. The range of relative humidity is from 20 and 25% minimum to 90 and 95%, plus or minus 5% and within a minimum and maximum dewpoint range of 40° to 90°F. The electric energy requirements of the largest unit consist of about 5.8 net KW for the lamps, a 2 HP compressor motor, a 1/3 HP fan motor and a 1 KW resistance heater. The inside area is 60 ft.² and the inside volume is 420 ft.³.